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Effects of nutrient solution and substrate on *Limnocharis flava* performance in hydroponic systems

RIZKA NOVI SESANTI[1,2], EDI PURWANTO[3,♥], SAMANHUDI[3], SUDADI[4]
[1]Doctoral Program of Agricultural Science, School of Graduates, Universitas Sebelas Maret. Jl. Ir. Sutami 36A Surakarta 57126, Central Java, Indonesia
[2]Program of Horticulture Production Technology, Department of Food Crop Cultivation, Politeknik Negeri Lampung. Jl. Soekarno Hatta, No. 10, Rajabasa, Bandar Lampung 35141, Lampung, Indonesia
[3]Department of Agrotechnology, Faculty of Agriculture, Universitas Sebelas Maret. Jl. Ir. Sutami 36A Surakarta 57126, Central Java, Indonesia. Tel./fax.: +62-271-663375, ♥email: edipurwanto@staff.uns.ac.id
[4]Department of Soil Science, Faculty of Agriculture, Universitas Sebelas Maret. Jl. Ir. Sutami 36A Surakarta 57126, Central Java, Indonesia

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Abstract. *Sesanti RN, Purwanto E, Samanhudi, Sudadi. 2025. Effects of nutrient solution and substrate on* Limnocharis flava *performance in hydroponic systems. Asian J Agric 9: 590-597. Limnocharis flava* is a promising aquatic vegetable for substrate-based hydroponic cultivation. However, the optimal combination of nutrient concentrations and substrate types to maximize growth under hydroponic conditions remains unclear. This study evaluated five nutrient solution concentrations (0, 0.8, 1.6, 2.4, and 3.2 dS m^{-1}) and three substrate types (volcanic sand, rice husk charcoal, and a 1:1 mixture) in a Randomized Complete Block Design (RCBD) with three replications. Nutrient concentrations of 0.8 and 1.6 dS m^{-1} produced the highest plant height (28.48 cm and 28.20 cm), number of leaves (11.31 and 11.03), shoot dry weight (4.61 g and 4.74 g), root fresh weight (13.20 g and 12.43 g), and root dry weight (0.76 g and 0.74 g). Both lower and higher concentrations inhibited growth, indicating optimal thresholds for nutrient uptake. Chlorophyll a, b, and total chlorophyll contents were similar across the 0.8-3.2 dS m^{-1} range, but consistently higher than the control. The leaf greenness index showed a significant interaction between nutrient concentration and substrate type, with the highest value at 2.4 dS m^{-1} in the mixed substrate. A nutrient concentration of 1.6 dS m^{-1} produced the best overall performance. Based on these results, a combination of 1.6 dS m^{-1} nutrient solution and a 1:1 mixture of volcanic sand and rice husk charcoal is recommended for the cultivation of *L. flava*. These findings establish baseline guidelines for hydroponic cultivation of *L. flava* and highlight its potential to advance precision hydroponics for indigenous vegetables, thereby contributing to food security and sustainable agriculture.

Keywords: Aquatic vegetable, biosynthesis, chlorophyll, electrical conductivity, substrate

INTRODUCTION

Indonesia is renowned for its rich biodiversity, which includes a vast array of indigenous plants with untapped potential to enhance food security and nutritional diversity. Among these, *Limnocharis flava* (L.) Buchenau (yellow velvetleaf) emerges as a particularly promising candidate due to its unique adaptability and nutritional profile. This aquatic vegetable thrives in waterlogged conditions, a trait that sets it apart from many conventional leafy vegetables, which often fail in marginal wetlands. *Limnocharis flava* provides higher levels of key nutrients compared to widely consumed leafy vegetables such as spinach (*Spinacia oleracea* L.), water spinach (*Ipomoea aquatica* Forssk.), and lettuce (*Lactuca sativa* L.). On a fresh-weight basis, *L. flava* contains approximately 3.5 g of protein per 100 g, which is about 30% higher than spinach (2.7 g) and more than twice that of lettuce (1.4 g). Its calcium content (~140 mg/100 g) also surpasses that of spinach (99 mg), water spinach (77 mg), and lettuce (33 mg), while its iron concentration (~5.2 mg/100 g) is nearly double that of spinach (2.7 mg) and more than triple that of lettuce (0.9 mg). In addition, *L. flava* exhibits a robust antioxidant profile, with total phenolic content exceeding 40 mg GAE/g extract and an IC_{50} for DPPH scavenging of 35-40 μg/mL, values that are comparable to or even superior to those reported for common leafy vegetables (Susila et al. 2012; Harich et al. 2019; Dylag et al. 2023; Saikia et al. 2023; Sudirman et al. 2023). Despite these advantages, its cultivation remains limited to regions such as Sumatra and West Java, constraining its accessibility and economic potential (Saupi et al. 2020; Chatara et al. 2023; Putra et al. 2023).

To expand its utilization, cultivation methods that mimic its natural aquatic environment while ensuring yield stability are needed. Conventional systems are inadequate, whereas substrate-based hydroponics offers precise nutrient and water management, reduced soil-borne risks, and suitability for urban agriculture (Perkasa and Petropoulos 2020; Pomoni et al. 2023; Fathidarehnijeh et al. 2024). However, the effectiveness of hydroponics is highly dependent on nutrient solution concentration and substrate type, both of which directly influence plant physiology, chlorophyll content, and stress tolerance (Neocleous et al. 2020; Łaźny et al. 2021; Yang et al. 2021; Azmin et al. 2022).

Previous studies on leafy vegetables have reported inconsistent responses to nutrient and substrate conditions. Spinach benefited from higher nutrient levels (3.4 dS m^{-1}), whereas lettuce exhibited optimal growth at moderate nutrient solution concentration (1.3 dS m^{-1}), and *Cichorium* *spinosum* L. showed minimal response (Gillespie et al. 2021; Kappel et al. 2021; Voutsinos-Frantzis et al. 2022). Similarly, cocopeat improved the yield of spinach but was less effective for lettuce, for which inorganic substrates such as perlite performed better (Machado et al. 2021; Nerlich and Dannehl 2021). These differences indicate that substrate–nutrient interactions are species-specific and cannot be generalized across all leafy vegetables.

For *L. flava*, no systematic studies exist under hydroponic conditions. Current recommendations are extrapolated from other crops, overlooking its adaptations to aquatic environments, which may alter responses to nutrient imbalances and root zone conditions. The critical interaction between nutrient concentration and substrate type is a determinant of nutrient uptake and root health remains unexplored. Therefore, this study addresses this gap by evaluating the effects of nutrient solution concentrations (0-3.2 dS m^{-1}) and substrate types (volcanic sand, rice husk charcoal, and a 1:1 mixture) on the growth and chlorophyll content of *L. flava*. The findings aim to establish evidence-based guidelines for hydroponic cultivation of *L. flava*, contributing to its commercial viability, sustainable agriculture, and broader utilization of indigenous aquatic crops.

MATERIALS AND METHODS

Study area

This study was conducted in the greenhouse of the Faculty of Agriculture, Universitas Sebelas Maret, Surakarta, Central Java, Indonesia (altitude 131 m above sea level; coordinates 7°33′41.8″ S and 110°51′32.36″ E) from August to October 2024. The greenhouse was covered with UV-stabilized polyethylene film and had natural ventilation through side openings. Environmental parameters during the experiment were as follows: light intensity of 680-850 µmol m^{-2} s^{-1} (measured at midday) and a natural photoperiod of 12.3-12.5 h. The average temperature and relative humidity during the experiment are shown in Figure 1.

Experimental design and treatments

This study was conducted using a factorial experiment that was arranged in a Randomized Complete Block Design (RCBD) with three replications. Factor A was the nutrient solution concentrations (0, 0.8, 1.6, 2.4, and 3.2 dS m^{-1}), and factor B was the substrate type (volcanic sand, rice husk charcoal, and a 1:1 mixture). This study had fifteen treatments replicated three times, resulting in 45 experimental units. Each experimental unit contained six plants, and three plants were sampled.

Procedures

Preparation of the hydroponic installation of the floating raft system without an aerator

The hydroponic installation of the floating raft system without an aerator was prepared using 45 plastic boxes. The top of each box was covered with styrofoam and perforated according to a planting distance of 20×20 cm, accommodating six plants per box. The layout was divided into three groups according to the number of replicates, with each replicate containing 15 boxes. Each box was filled with the designated substrate treatment, namely volcanic sand, husk charcoal, or a 1:1 mixture of volcanic sand and husk charcoal. The substrate was arranged to a depth of 15 cm, after which the nutrient solution was applied until reaching 2 cm above the substrate surface. The system was operated without aeration to mimic the natural waterlogged conditions in which *L. flava* typically grows, making it simple and low cost. Such a design minimizes investment and management requirements, thereby offering a more accessible option for small-scale farmers and supporting broader adoption of sustainable hydroponic practices.

Planting of Limnocharis flava *seedlings*

Limnocharis flava seedlings were obtained from Semarang Regency. The seedlings used were 15 cm tall, with a total of 3 leaves. Planting the seedlings was done by placing the seedlings in the planting holes that had been provided in the hydroponic installation.

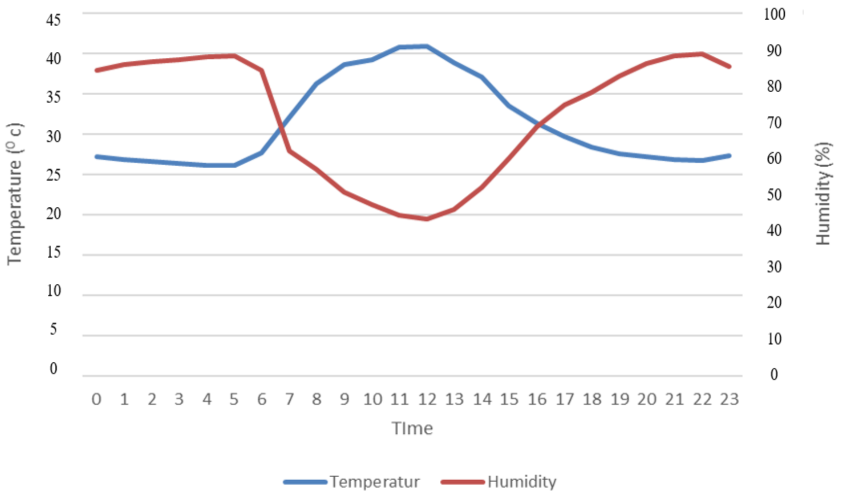

Figure 1. Average temperature and relative humidity in the greenhouse from August to October 2024

Nutrient treatment

The hydroponic nutrient solution was formulated to contain 180 ppm NO_3^-, 37 ppm NH_4^+, 66 ppm P, 286 ppm K, 154 ppm Ca, 66 ppm Mg, and 122 ppm S, plus 40 g Vitaflex™ micronutrient mix, in 5 L of concentrated stock solution. Stock Solution A contained nitrate, ammonium, potassium, calcium, and micronutrients, without sulfate or phosphate salts. Stock Solution B contained magnesium, sulfate, and phosphate salts. Solutions were diluted to treatment and adjusted to 6.0±0.2 pH daily using 1 N HCl or NaOH. Nutrient solution concentration was monitored with a calibrated EC meter (Hanna HI 98301). Nutrient solution treatments (0, 0.8, 1.6, 2.4, 3.2 dS m^{-1}) were obtained by adding water to the nutrient stock solution.

Substrate

Volcanic sand (3-5 mm) was collected from volcanic deposits, while rice husk charcoal was produced by pyrolysis at 400°C under limited oxygen. Mixed substrates were prepared volumetrically.

Maintenance and harvesting

Plant maintenance is done by checking the concentration of nutrient solution and pH every day using an EC and pH meter. If the nutrient solution concentration and pH are not appropriate, the feeding treatment is adjusted. Pest and disease control was carried out without the use of pesticides by picking up pests by hand or removing diseased plants. Harvesting was done when *L. flava* was 28 days after planting (DAP). Harvesting was done by pulling out *L. flava* from the planting hole and collecting it into a container for observation.

Sample preparation and analysis

Growth measurement

The observation variables included plant height (cm) measure with ruler, number of leaves (leaf), is counted manually on fully opened leaves, leaf area (cm^2) measure with Leaf Area Measurement., plant fresh weight (g), plant dry weight (g), root fresh weight (g), root dry weight (g) measure with analytical balance.

Chlorophyll and SPAD measurement

Leaf greenness index was measure with SPAD, and chlorophyll content was calculated using the following formula developed by Arnon (1949)

$$\text{Chlorophyll A} = (12.7 \times A\,663 - 2.69 \times A\,645) \times v/w \times 1000$$

$$\text{Chlorophyll B} = (22.9 \times A\,645 - 4.68 \times A663)\ x\ v/w \times 1000$$

$$\text{Total chlorophyll} = (20.2 \times A645) + (8.02 \times A663) \times v/w \times 1000$$

Where:
v: Supernatant volume
w: Leaf weight

Data analysis

The collected data were analyzed using Analysis of Variance (ANOVA) using the Factorial procedure in a Randomized Complete Block Design (RCBD) available in SPSS 26 software. If the calculated F value is significant, continue with Duncan's Multiple Range Test (DMRT) at the 5% level. DMRT was chosen for its higher sensitivity in detecting differences among means in experiments with small replication numbers, making it suitable for horticultural studies with limited sample sizes (Gomez and Gomez 1984)

RESULTS AND DISCUSSION

Growth and biomass accumulation

The application of varying nutrient solution concentration levels significantly influenced the growth and biomass accumulation of *L. flava*. Growth parameters such as plant height, number of leaves, and leaf area showed an optimum at 0.8-1.6 dS m^{-1}, while a noticeable decline was observed beyond 2.4 dS m^{-1} (Table 1). This pattern suggests that *L. flava* performs best under low to moderate nutrient supply, aligning with previous findings on *L. sativa,* which reported optimal growth at 0.9-1.3 dS m^{-1} (Hosseini et al. 2021; Kappel et al. 2021). Plant height, leaf number, and leaf area increased significantly within the range of 0.8-1.6 dS m^{-1}. Biomass data supported this trend, with the highest plant fresh weight (55.77 g) and root fresh weight (13.20 g) recorded at 0.8 dS m^{-1}. Although root dry weight remained stable from 0.8 to 2.4 dS m^{-1}, both low and higher nutrient solution concentrations resulted in significant decreases in root and plant biomass, indicating stress due to nutrient imbalance. These reflect the physiological response of *L. flava* to nutrient availability. Low nutrient supply results in stunted growth and a reduction in fresh biomass of herbaceous plants by nearly 50% (Fimbres-Acedo et al. 2022). In contrast, excessively high nutrient solution concentration levels (>2.4 dS m^{-1}) tend to disrupt ionic balance, reduce osmotic potential, and interfere with nutrient absorption, which ultimately limits biomass accumulation (Soufi et al. 2023).

Therefore, the optimal nutrient solution concentration range for *L. flava* growth in hydroponic systems is between 0.8-1.6 dS m^{-1}, with growth performance declining sharply above 2.4 dS m^{-1}. Substrate type did not significantly affect most vegetative traits, suggesting that all tested media provided sufficient aeration and water retention. Nonetheless, husk charcoal showed a slight advantage in supporting plant and root fresh weight. This supports previous research indicating that biochar-based media enhance plant performance under suboptimal nutrient or salinity conditions by improving cation exchange capacity and buffering against salt stress (Nurhidayati et al. 2022; Zhu et al. 2024; Sahin et al. 2025). Recent evidence also demonstrates that biochar substrates improve pore structure and nutrient-use efficiency in hydroponic systems, making them globally relevant for sustainable cultivation (Ighalo et al. 2025; Natalli et al. 2024).

Several recent global studies have confirmed that moderate nutrient solution concentration in hydroponic systems enhances the growth, yield, and quality of leafy vegetables (Adhikari et al. 2022; Do Carmo et al. 2024; Martinez-Moreno et al. 2024). Moreover, recent studies on hydroponically grown leafy vegetables, including kale, collard, and broccoli, have demonstrated that excessive nutrient solution concentration can negatively affect plant performance (Tobassum et al. 2023; Yang et al. 2024). Excessive nutrient solution concentration in hydroponic systems impairs photosynthesis, reduces biomass accumulation, and decreases yield, while moderate nutrient solution concentration promotes optimal growth and nutritional quality. These findings collectively highlight the critical importance of precise management of both nutrient solution concentration to maximize productivity and performance in hydroponically grown leafy vegetables.

Chlorophyll content and leaf greenness index

Nutrient solution concentrations (0.8-3.2 dS m^{-1}) did not significantly affect chlorophyll a, b, or total chlorophyll content in *L. flava*. However, all nutrient-supplemented treatments resulted in significantly higher chlorophyll content compared to the control (0 dS m^{-1}), which showed the lowest values (Table 2). This indicates that the presence of essential nutrients, especially nitrogen (N), magnesium (Mg), and iron (Fe), is crucial for chlorophyll biosynthesis (Li et al. 2022; Nasar et al. 2022; Lazarević et al. 2024; Mthiyane et al. 2024). Although increasing nutrient solution concentration levels did not further increase chlorophyll content above 0.8 dS m^{-1}, this stable value may be due to ion antagonism under high salinity conditions. Specifically, increased nutrient solution concentration can lead to the accumulation of potassium (K), which inhibits the uptake of Mg, a key element in chlorophyll structure (Currey et al. 2019). This ion competition at higher nutrient solution concentration levels can inhibit nutrient uptake, resulting in stagnant chlorophyll levels, as supported by previous studies (Nkcukankcuka et al. 2022; Papadakis et al. 2023). Given the absence of chlorophyll increases above 0.8-1.6 dS m^{-1}, this range appears optimal for hydroponic cultivation of *L. flava*. Higher concentrations provide no additional physiological benefits and may ultimately lead to nutrient imbalance or chlorosis over time. Substrate type also showed no significant effect on chlorophyll parameters, with all tested media producing comparable values.

Leaf greenness, estimated using the Soil Plant Analysis Development (SPAD) index, showed a significant interaction between nutrient concentration and substrate type (Table 3). The highest SPAD value (53.53) was recorded in the 2.4 dS m^{-1} treatment combined with a 1:1 mixture of volcanic sand and rice husk charcoal. Statistically similar values were also observed in the 1.6 and 2.4 dS m^{-1} combinations with volcanic sand. These treatments support optimal chlorophyll synthesis and nitrogen use efficiency, which are closely correlated with SPAD readings and plant physiological performance (Hou et al. 2021; Li et al. 2021). SPAD values without nutrients (0 dS m^{-1}) ranged from 9.03 to 11.60, indicating severe chlorophyll deficiency in all substrates. In contrast, the use of nutrient concentrations of 0.8-2.4 dS m^{-1} resulted in SPAD values between 28.46 and 50.96, with the mixed substrate consistently outperforming the single substrate treatments. This indicates a synergistic effect between volcanic sand and rice husk charcoal in increasing nutrient retention and root aeration, corroborating the findings of Olasehinde (2025).

A synthesis of these results reveals a trend where actual chlorophyll concentrations remained stable across nutrient solution concentration treatments ≥0.8 dS m^{-1}. In comparison, SPAD values increased up to a threshold nutrient solution concentration (1.6-2.4 dS m^{-1}), then reached saturation or declined slightly. This difference is due to physiological and anatomical adaptations, rather than changes in pigment content. Although SPAD readings are widely used as proxies for chlorophyll and nitrogen content, they are also influenced by factors such as mesophyll thickness, chloroplast density, and leaf optical properties (El-Hendawy et al. 2022; Shi et al. 2024; Zhang et al. 2024). Under high nutrient solution concentration conditions, plants adapt by increasing the palisade and mesophyll cell layers, which alters light transmission through the leaf and results in artificially increased SPAD values (Xiong et al. 2015; Liu et al. 2024). This adaptive mechanism allows plants to maintain photosynthetic efficiency despite nutrient stress, highlighting the importance of interpreting SPAD data in conjunction with biochemical chlorophyll analysis.

Table 1. Effects of nutrient solution concentrations and substrate types on growth parameters and biomass of *Limnocharis flava* at 28 days after planting (DAP)

Treatment	Plant height (cm)	Number of leaf (leaves)	Leaf area (cm^2)	Plant fresh weight (g)	Plant dry weight (g)	Root fresh weight (g)	Root dry weight (g)
Concentration (dS m^{-1})							
0	19.94±1.77 c	5.32±0.21 c	127.86±16.3 d	9.66 ± 1.56 d	0.83 ± 0.17 c	4.88 ± 0.05 d	0.32 ± 0.04 b
0.8	28.48±1.09 a	11.31±0.67 a	482.02±54.4 a	55.77 ± 4.11 a	4.61 ± 0.84 a	13.20 ± 1.55 a	0.76 ± 0.05 a
1.6	28.20±0.22 a	11.03±0.39 a	356.68±34.2 b	46.53 ± 11.33 b	4.74 ± 0.49 a	12.43 ± 4.27 ab	0.74 ± 0.17 a
2.4	25.96±1.39 ab	10.28±0.63 ab	262.83±54.8 c	32.83 ± 3.02 c	3.61 ± 0.41 b	10.92 ± 2.24 b	0.64 ± 0.17 a
3.2	23.48±1.62 b	9.03±0.23 b	230.09±26.3 c	27.47 ± 2.89 c	3.26 ± 0.40 b	7.93 ± 1.06 c	0.41 ± 0.02 b
Substrate							
Volcanic sand	25.70±3.41 a	9.07±2.10 a	269.48±125.8 a	30.52±15.44 b	3.39 ± 1.57 a	8.07 ± 2.42 c	0.51 ± 0.16 a
Husk charcoal	24.96±4.18 a	9.57±2.65 a	295.87±126.0 a	37.17±21.18 a	3.22 ± 1.60 a	11.63 ± 4.76 a	0.62 ± 0.25 a
Volcanic sand+ husk charcoal (1:1)	24.98±3.62 a	9.54±2.60 a	310.33±158.0 a	35.65±17.73 ab	3.63 ± 1.71 a	9.91 ± 3.52 b	0.58 ± 0.22 a
CV (%)	10.91	15.10	15.10	22.80	19.73	20.22	25.40

Note: The numbers followed by the same letters and columns showed no significant difference based on the DMRT test at a level of 5%

Table 2. Effects of nutrient solution concentrations and substrate types on chlorophyll a, chlorophyll b, and total chlorophyll contents of *Limnocharis flava* at 28 days after planting (DAP)

Treatment	**Chlorophyll A content (mg g-1)**	**Chlorophyll B content (mg g-1)**	**Chlorophyll total content (mg g-1)**
Concentration (dS m^{-1})			
0	0.043±0.00 b	0.015±0.00 b	0.058±0.00 b
0.8	0.145±0.01 a	0.079±0.03 a	0.224±0.03 a
1.6	0.157±0.00 a	0.087±0.01 a	0.244±0.01 a
2.4	0.149±0.00 a	0.077±0.01 a	0.226±0.01 a
3.2	0.167±0.01 a	0.109±0.00 a	0.276±0.00 a
Substrate			
Volcanic sand	0.130±0.04 a	0.088±0.04 a	0.218±0.09 a
Husk charcoal	0.136±0.05 a	0.065±0.03 a	0.202±0.08 a
Volcanic sand+ husk charcoal (1:1)	0.130±0.05 a	0.066±0.03 a	0.197±0.08 a
CV (%)	19.52	56.88	29.87

Note: The numbers followed by the same letters and columns showed no significant difference based on the DMRT test at a level of 5%

Table 3. Effects of nutrient solution concentrations and substrate types on the leaf greenness index of *Limnocharis flava* at 28 days after planting (DAP)

Treatment	**Leaf greenness index (SPAD)**
0 dS.m^{-1} x volcanic sand	9.36±0.81 f
0.8 dS.m^{-1} x volcanic sand	42.76±1.19 d
1.6 dS.m^{-1} x volcanic sand	49.23±2.02 abc
2.4 dS.m^{-1} x volcanic sand	50.96±2.21 ab
3.2 dS.m^{-1} x volcanic sand	46.00±4.50 bcd
0 dS.m^{-1} x husk charcoal	9.03±3.05 f
0.8 dS.m^{-1} x husk charcoal	28.46±1.85 e
1.6 dS.m^{-1} x husk charcoal	43.83±3.05 cd
2.4 dS.m^{-1} x husk charcoal	43.13±1.42 cd
3.2 dS.m^{-1} x husk charcoal	46.13±6.38 bcd
0 dS.m^{-1} x volcanic sand+husk charcoal (1:1)	11.60±2.47 f
0.8 dS.m^{-1} x volcanic sand+husk charcoal (1:1)	43.16±3.80 cd
1.6 dS.m^{-1} x volcanic sand+husk charcoal (1:1)	45.46±1.30 bcd
2.4 dS.m^{-1} x volcanic sand+husk charcoal (1:1)	53.53±6.46 a
3.2 dS.m^{-1} x volcanic sand+husk charcoal (1:1)	47.06±1.10 bcd
CV (%)	8.80

Note: The numbers followed by the same letters and columns showed no significant difference based on the DMRT test at a level of 5%

Visual aspect

Successful vegetable production is not only assessed based on agronomic parameters but also considers visual aspects of the plant, such as leaf color, size, and damage level. In this study, variations in nutrient solution concentration affected the visual appearance of *L. flava*, particularly leaf color, size/shape, and damage (Figure 2). The 0 dS m^{-1} nutrient solution treatment caused yellowing of the leaves, likely due to nutrient deficiencies, especially N, Mg, and Fe, which are essential for chlorophyll biosynthesis (Ding et al. 2018). Nutrient deficiencies directly reduce chlorophyll a and b content and the leaf greenness index (Tables 2 and 3). In contrast, leaves in the 2.4 dS m^{-1} and 3.2 dS m^{-1} treatments remained green but exhibited edge damage, visible as drying of the leaf margins. At 3.2 dS m^{-1}, leaves not only showed margin damage but also became smaller, elongated, and stiff.

Increasing nutrient concentrations can stimulate plant growth up to a certain threshold. However, exceeding the plant's physiological tolerance can lead to osmotic imbalance and ionic toxicity. Common visual symptoms include leaf margin necrosis (tip burn), interveinal chlorosis, and premature leaf drop (Yap et al. 2022). Tip burn results from impaired calcium transport to meristematic tissues, often exacerbated by rapid growth induced by excess nutrients. High nutrient concentrations also increase the osmotic pressure around roots, inhibiting water uptake and causing local leaf dehydration, which physiologically mimics drought, even under an adequate water supply. Excessive ions, such as sodium or ammonium, may further interfere with enzyme activity and damage cell structures (Zhu et al. 2024).

The change in leaf shape to lanceolate at 3.2 dS m^{-1} is likely due to high N and P concentrations. Excess nitrogen tends to reduce overall leaf expansion, increase vein density, and redirect growth toward internal structure reinforcement, resulting in smaller, stiffer leaves. Excess phosphorus can increase the leaf length-to-width ratio, producing elongated, narrow, lanceolate leaves (Zhang et al. 2024).

Although the findings of this study are specific to *L. flava*, they provide valuable insights into broader hydroponic cultivation principles. The unique adaptability of *L. flava* to waterlogged conditions and its interactions with different substrates and nutrient concentrations cannot be directly generalized to all hydroponic crops. Nevertheless, the methodological approaches and nutrient management strategies presented here are transferable to other species with similar ecological requirements. This highlights that while the physiological responses may vary among crops, the underlying principles of hydroponic system optimization particularly in terms of substrate and nutrient interactions remain widely applicable.

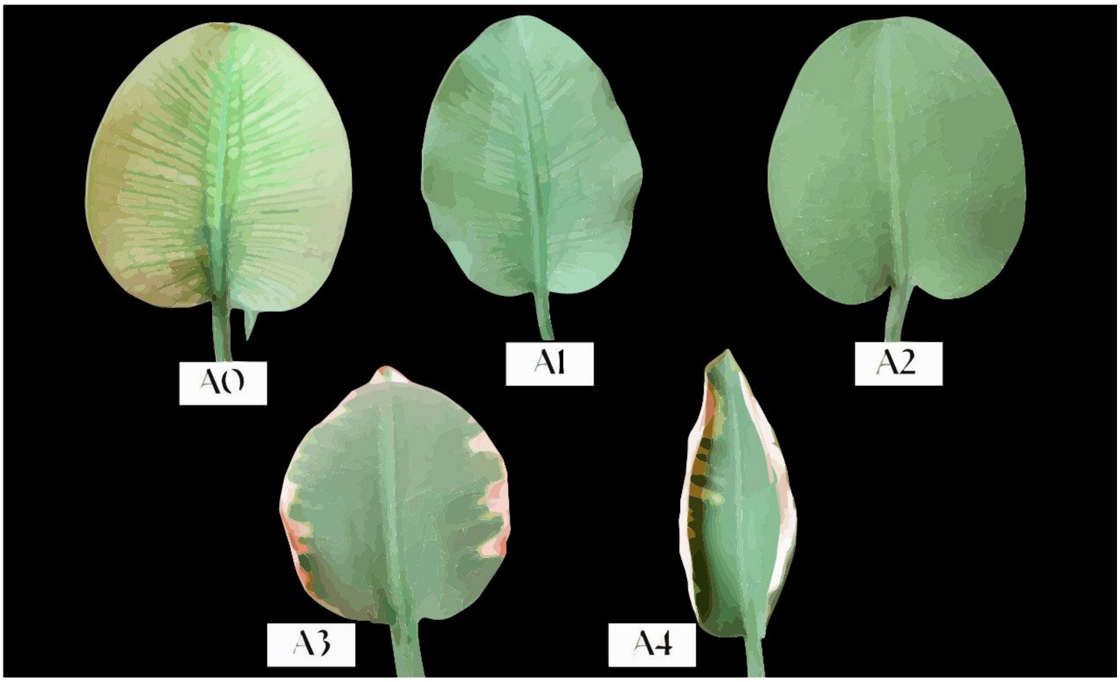

Figure 2. Visual appearance of *Limnocharis flava* leaves at increasing nutrient solution concentrations (A0=0, A1=0.8, A2=1.6, A3=2.4, A4=3.2 dS m^{-1}). Leaves at A0 are chlorotic, A1 shows leaves with uneven greenness, A2 exhibits healthy green leaves, A3 displays burnt edges, and A4 shows lanceolate morphology. These labels illustrate the effect of nutrient solution concentration on leaf greenness and morphology

In conclusion, this study demonstrated that optimal growth, biomass accumulation, and physiological quality of *L. flava* in a hydroponic system were achieved at nutrient solution concentrations of 0.8-1.6 dS m^{-1}. Concentrations exceeding 2.4 dS m^{-1} significantly reduced plant performance and caused stress symptoms such as shoot burns and leaf deformation. Although substrate type did not significantly affect most vegetative parameters, a mixed substrate of volcanic sand and rice husk charcoal consistently increased fresh biomass and SPAD index, indicating improved nutrient retention and root-zone conditions. Chlorophyll content remained relatively stable across nutrient solution treatments ≥0.8 dS m^{-1}, while SPAD values increased with nutrient concentration until reaching a threshold, reflecting biochemical and anatomical adaptations. These findings suggest that a nutrient solution of 1.6 dS m^{-1} combined with a mixed substrate provides the most favorable conditions for hydroponic cultivation of *L. flava*. This low-input combination is ideal for cost-effective, urban farming, offering a sustainable solution for leafy vegetables. While these results are specific to *L. flava*, the methodological insights and nutrient management strategies presented here are transferable to other hydroponic crops with comparable ecological traits.

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