

Media Hydraulics Govern Pakchoi (*Brassica chinensis*) Growth under Floating Sub-irrigation

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ABSTRACT

Floating vegetable cultivation can reduce production constraints in wetland areas, but its performance depends on the capacity of planting and suction media to regulate capillary water supply in the root zone. This study evaluated the effects of media hydraulics on root-zone moisture, growth, and yield of pakchoi under a floating sub-irrigation system. A greenhouse experiment was arranged using two planting media, namely soil:rice husk charcoal:manure (1:1:1) and soil:manure (3:1), combined with two suction media, namely crushed tile particles and fabric wick, with three replications. Hydraulic conductivity, bulk density, root-zone moisture dynamics, plant height, leaf number, and fresh biomass were observed. The soil:manure medium had lower hydraulic conductivity ($4.23 \times 10^{-5} \text{ cm s}^{-1}$) and higher bulk density (0.97 g cm^{-3}), indicating greater water retention capacity than the more porous medium. The combination of soil:manure and crushed tile suction media produced the best crop response, with plant height of 22.17 cm, 10 leaves plant⁻¹, and fresh biomass of 86.21 g plant⁻¹. These results indicate that floating sub-irrigation performance is governed by the balance between capillary water supply and root-zone moisture retention. The system can be developed as a passive, low-energy irrigation technology for wetland vegetable cultivation.

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1. INTRODUCTION

Agricultural water management has become a strategic issue because climate change intensifies uncertainty in water availability, increases the frequency of hydrological extremes, and alters horticultural production patterns in vulnerable regions. Seasonal drought reduces water-use efficiency and restricts crop growth, whereas floods and prolonged inundation limit conventional soil-based vegetable cultivation by reducing root aeration and destabilizing the rooting environment. Recent reviews indicate that irrigation management should no longer be understood only as the application of water, but as an adaptation strategy that integrates crop demand, growing-media properties, microclimate, and energy efficiency (Ahmed et al., 2023; Gabr et al., 2024).

In wetland environments, the water-management problem is more complex because water may be abundant but not necessarily available in a form suitable for plant roots. Waterlogging can reduce oxygen diffusion, restrict nutrient uptake, and create unstable rhizosphere conditions for short-cycle leafy vegetables. Adaptive cultivation systems, including floating agriculture and floating wetland islands, are therefore increasingly considered for maintaining crop production in inundated environments. Previous studies have shown that floating agriculture can serve as a climate-resilient option for waterlogged areas, although agronomic performance depends strongly on crop choice, growing media, water quality, and system design (Karmaker et al., 2023; Carrillo et al., 2026).

The main challenge in wetland vegetable cultivation is not merely water supply, but the regulation of water so that it remains stable, non-excessive, and accessible to active roots. Conventional systems often fail to meet this requirement because the growing media are directly exposed to fluctuating water levels, whereas surface irrigation is inefficient for container or floating-platform cultivation. In pakchoi (*Brassica chinensis*), stable root-zone moisture is critical because leaf formation, canopy expansion, and fresh biomass accumulation are sensitive to water availability during the vegetative stage. The productivity of protected vegetable systems is therefore closely linked to moisture monitoring and irrigation control in the root zone (Thompson et al., 2020).

Water-saving irrigation technologies have been developed to maintain root-zone moisture while reducing non-productive water losses. Sub-irrigation, wick irrigation, capillary mats, and closed irrigation systems deliver water from below and rely on capillary movement through porous media. Compared with surface irrigation, capillary-based irrigation can reduce runoff, lower the need for manual watering, and deliver water closer to the root zone. However, the effectiveness of such systems depends on the compatibility between the planting medium and the suction medium because both components regulate hydraulic conductivity, water-storage capacity, and moisture distribution within the media profile (Semananda et al., 2018; Vahabi Mashhor et al., 2020).

A specific solution for wetland vegetable cultivation is floating sub-irrigation, in which a water reservoir beneath a floating platform is connected to the planting medium through a suction or wick component. Water moves passively from the reservoir into the pot through capillary action, reducing reliance on pumps or intensive manual irrigation. In this configuration, the suction medium functions as the water-transport pathway, whereas the planting medium serves as the storage matrix and root-growth environment. Classic soil-water-flow theory indicates that capillary rise, sorptivity, and hydraulic conductivity are key parameters controlling the rate and stability of water movement through porous media (Richards, 1931; Philip, 1957; van Genuchten, 1980; Hillel, 2004).

The physical properties of the planting medium are also decisive for the performance of floating sub-irrigation. A medium with high hydraulic conductivity can transmit water rapidly but may not retain moisture sufficiently in the upper root zone. Conversely, a denser medium with finer pore distribution can retain water longer, although water movement may be slower. Recent studies on soil amendments and biochar emphasize that organic and porous materials can modify bulk density, porosity, hydraulic properties, and plant-available water, thereby affecting water retention and root-zone stability (Razzaghi et al., 2020; Acharya et al., 2024).

The literature indicates that floating sub-irrigation has a strong scientific basis as an adaptive technology, but the relationship between media hydraulics, root-zone moisture stability, and crop response remains insufficiently explained. Many studies on water-saving irrigation emphasize water productivity or crop yield, while fewer studies explain how planting media and suction media jointly control water distribution in floating systems. Therefore, an approach that combines hydraulic characterization, moisture dynamics, and plant growth response is needed to clarify the mechanism behind crop performance under passive sub-irrigation (Semananda et al., 2018; Wang et al., 2022).

This study aimed to evaluate the effects of planting media and suction media on hydraulic properties, root-zone moisture dynamics, growth, and yield of pakchoi under a floating sub-irrigation system. The novelty of the study lies in using media hydraulics as a mechanistic basis for explaining passive floating irrigation performance. The study hypothesized that a planting medium with greater water-retention capacity, combined with a suction medium capable of stable capillary transport, would produce more stable root-zone moisture and better pakchoi growth. The scope of the study was limited to greenhouse conditions, four media combinations, hydraulic-property measurements, root-zone moisture observations, vegetative growth, and pakchoi fresh biomass.

2. MATERIALS AND METHODS

2.1. Study site and experimental period

The experiment was conducted in a greenhouse at the Department of Agricultural Technology, Faculty of Agriculture, Universitas Sriwijaya, Indralaya, Indonesia. The study was carried out for three months in 2015 using pakchoi (*Brassica chinensis*) as the test crop. Pakchoi was selected because it is a short-cycle leafy vegetable, responds rapidly to root-zone water availability, and is suitable for evaluating passive irrigation performance under controlled cultivation conditions.

The research activities included preparation of the floating sub-irrigation system, seedling production, transplanting, moisture monitoring, plant-growth measurement, and harvest evaluation. Greenhouse air temperature and relative humidity were monitored using a thermohygrometer at 08:00, 13:00, and 16:00 to support interpretation of moisture dynamics and crop growth.

The use of the 2015 dataset is justified by the controlled nature of the original greenhouse experiment and the continued relevance of the treatment structure for evaluating passive floating sub-irrigation. The delay in publication was caused by prolonged internal coordination among the authors regarding formal authorization to use and further process the archived numerical research data. No follow-up validation experiment was conducted

after the original data collection; therefore, the findings are interpreted within the original greenhouse conditions and this limitation is explicitly acknowledged.

2.2. Experimental design and treatments

The experiment was arranged as a 2×2 factorial treatment structure with three replications. The first factor was planting medium, consisting of A1 and A2. The second factor was suction medium, consisting of C1 and C2. A1 was a mixture of soil, rice husk charcoal, and manure at a ratio of 1:1:1, whereas A2 was a mixture of soil and manure at a ratio of 3:1. C1 was crushed tile particles passing 30 mesh, whereas C2 was a fabric wick with an approximate cross-sectional area of 4 cm².

Each experimental unit consisted of one plastic pot containing one pakchoi plant. With four treatment combinations and three replications, the experiment therefore involved 12 experimental units and 12 observed plants in total. The individual plant in each pot was used as the observational unit for plant height, leaf number, and biomass variables.

The treatment structure was designed to evaluate how different hydraulic characteristics of planting media and suction media influence capillary transport, root-zone moisture stability, vegetative growth, and pakchoi yield.

Table 1. Treatment combinations of planting media and suction media under floating sub-irrigation

Code	Planting media	Suction media
A1C1	Soil : rice husk charcoal : manure (1:1:1)	Crushed tile (30 mesh)
A1C2	Soil : rice husk charcoal : manure (1:1:1)	Fabric wick (4 cm ²)
A2C1	Soil : manure (3:1)	Crushed tile (30 mesh)
A2C2	Soil : manure (3:1)	Fabric wick (4 cm ²)

2.3. Floating sub-irrigation system setup

The floating sub-irrigation system was designed as a passive irrigation unit that used capillary movement from a water reservoir to the planting medium. The system consisted of a water reservoir, floating platform, plastic pots, planting media, and suction media. The reservoir was constructed as a plot with dimensions of 70 cm × 50 cm × 40 cm and lined with plastic tarp to prevent leakage. A styrofoam platform was used to support the pots above the water surface.

Plastic pots with a height of 24 cm and a body diameter of 14 cm were modified by making a hole of approximately 1 cm at the center of the bottom part for installing the suction medium. Each suction medium was approximately 13 cm long, with 8 cm placed inside the pot and 5 cm extending outside the pot and remaining immersed in the reservoir water. This configuration allowed water to move passively from the reservoir into the planting medium through capillary action.

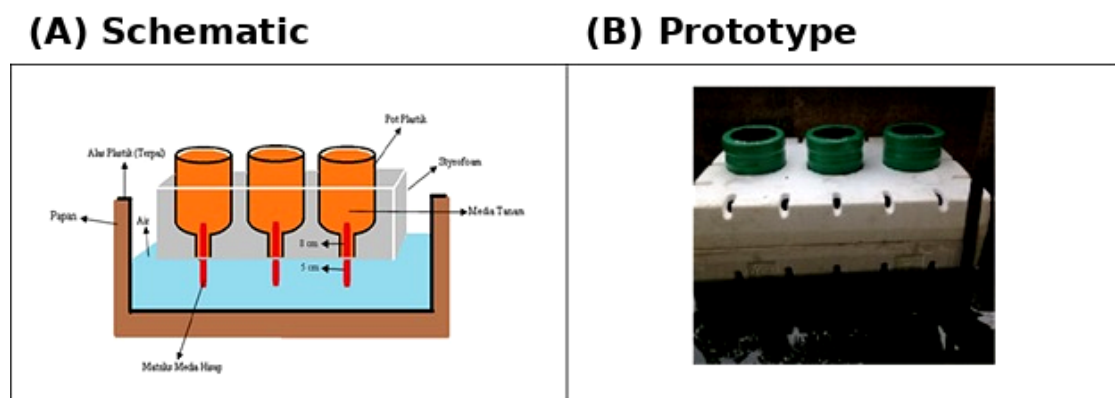


Figure 1. Schematic and prototype of the floating sub-irrigation system.

2.4. Plant preparation and crop management

Pakchoi seeds were first germinated in seedling trays using a soil-manure medium. Seedlings were transplanted into the treatment pots approximately three weeks after sowing, when the plants had developed 3-5 leaves. Before transplanting, the planting media were moistened to near saturation to standardize the initial water condition.

Plants were maintained under greenhouse conditions. Crop management consisted of pest control, foliar fertilization, and routine observation of plant condition. These practices were applied to maintain plant health so that treatment responses could be interpreted mainly in relation to planting medium, suction medium, and root-zone moisture stability.

2.5. Measurement of hydraulic properties

Hydraulic properties were measured to explain the ability of each medium to transmit and retain water. The observed parameters were hydraulic conductivity, bulk density, and total pore space. Hydraulic conductivity of the planting media and suction media was determined in the laboratory using a permeameter based on the falling-head method.

Bulk density was calculated as the ratio between dry mass and total occupied volume. A known mass of media was placed into a 100 mL graduated cylinder and gently tapped until the volume became stable. Total pore space was derived from the relationship between bulk density and particle density. These parameters were used to describe the pore structure associated with water retention, aeration, and capillary flow.

2.6. Root-zone moisture monitoring

Root-zone moisture was monitored to assess water distribution within the planting medium under floating sub-irrigation. Moisture content was measured using an EC-5 soil-moisture probe connected to an Em50 data logger. Sensor readings were calibrated using the gravimetric method to correct differences between sensor values and actual water content determined by oven drying.

Moisture observations were conducted before transplanting and during the vegetative stage. The pre-transplanting observation evaluated the ability of the suction media to lift water from the reservoir and stabilize the initial moisture profile. After transplanting, observations were conducted during early, middle, and late vegetative phases to evaluate the interaction among capillary supply, evaporation, and crop water uptake.

2.7. Plant growth and yield measurement

Plant growth was observed weekly during the vegetative period. The measured growth parameters were plant height and number of leaves. Plant height was measured from the stem base to the highest leaf point, whereas the number of leaves was counted as fully opened leaves per plant.

Harvesting was conducted at 33 days after transplanting. Plants were carefully removed from the pots to obtain the shoot and root components. The observed yield variables included fresh shoot biomass, dry shoot biomass, and dry root biomass. Fresh shoot biomass was weighed immediately after harvest, whereas dry biomass was obtained after oven drying at 75°C for 24 h.

2.8. Data analysis

Data were compiled according to the 2×2 factorial arrangement consisting of planting medium and suction medium, with three replications. Each pot containing one pakchoi plant was treated as one experimental unit for growth and biomass variables. Hydraulic-property and root-zone moisture time-series data were used to support mechanistic interpretation of water transmission, water retention, and root-zone moisture stability. Growth and yield variables were analyzed using the original replicate-level data and expressed as mean \pm standard error (SE; $n = 3$). Plant height and leaf number were analyzed separately for each weekly observation because growth responses changed over time.

Inferential analysis was conducted using factorial analysis of variance (ANOVA) for a 2×2 treatment arrangement in a randomized complete block design, with planting medium (A), suction medium (C), and their interaction (A \times C) as treatment sources and replication as the blocking factor. When ANOVA indicated significant effects, treatment means were compared using the least significant difference (LSD) test at the 5% significance level. Different lowercase letters in tables and figures indicate significant differences among treatment combinations at $p \leq 0.05$. All statistical values were calculated from the original primary replicate data, without modifying the primary observations.

3. RESULTS AND DISCUSSION

3.1. Hydraulic properties of planting media and suction media

The planting and suction media showed distinct hydraulic characteristics that were important for the ability of the floating sub-irrigation system to supply water to the pakchoi root zone. Planting medium A1, consisting of soil, rice husk charcoal, and manure at a ratio of 1:1:1, had a hydraulic conductivity of 9.20×10^{-5} cm s⁻¹, a bulk density of 0.36 g cm⁻³, and a total pore space of 87%. In contrast, planting medium A2, consisting of soil and manure at a ratio of 3:1, had lower hydraulic conductivity of 4.23×10^{-5} cm s⁻¹, higher bulk density of 0.97 g cm⁻³, and lower total pore space of 64%. These results indicate that A1 was more porous and permitted faster water movement, whereas A2 had a denser structure that could retain water longer in the root zone.

For the suction media, C2 fabric wick had a hydraulic conductivity of 2.48×10^{-3} cm s⁻¹, higher than C1 crushed tile particles at 1.80×10^{-3} cm s⁻¹. This value indicates that the fabric wick could transmit water more rapidly from the reservoir to the planting medium. However, the best plant response was not obtained from the treatment with the fastest suction medium. In capillary irrigation, the success of water supply depends not only on the capacity of the wick to lift water but also on the capacity of the planting medium to store, retain, and distribute water in a stable manner. Semananda et al. (2018) emphasized that capillary irrigation systems such as wicks,

mats, and sub-irrigated planters rely on capillary movement, but their effectiveness is strongly influenced by the properties of the growing media.

The findings are consistent with Vahabi Mashhor et al. (2020), who reported that sub-irrigated planter systems can improve water productivity because water is stored in a lower reservoir and delivered upward by capillary action. In the present study, A2C1 became the most favorable configuration because A2 provided greater water-retention capacity, whereas C1 supplied capillary water without excessive movement. Therefore, floating sub-irrigation performance was governed more by the balance between capillary supply and water retention than by high hydraulic conductivity alone.

Table 2. Hydraulic conductivity, bulk density, and total pore space of planting and suction media

Code	Treatment factor	Hydraulic conductivity (cm s-1)	Bulk density (g cm-3)	Total pore space (%)
A1	Soil : rice husk charcoal : manure (1:1:1)	9.20×10^{-5}	0.36	87
A2	Soil : manure (3:1)	4.23×10^{-5}	0.97	64
C1	Crushed tile, 30 mesh	1.80×10^{-3}	1.10	-
C2	Fabric wick, 4 cm ²	2.48×10^{-3}	0.63	-

3.2. Root-zone moisture stabilization before transplanting

Moisture dynamics before transplanting showed that the floating sub-irrigation system required a stabilization period to reach capillary equilibrium among the reservoir, suction medium, and planting medium. In all treatment combinations, moisture content tended to increase gradually and then moved toward a more stable condition. This pattern confirms that water from the reservoir could be transferred passively into the planting media through the suction media without external pressure or pumping.

The moisture profile also showed a vertical gradient. The lower part of the medium had higher moisture content because it was closer to the water source, whereas the upper layer had lower moisture content because it was more exposed to evaporation. This pattern is important for pakchoi cultivation because young roots require sufficient moisture but should not be exposed to excessive saturation that may restrict aeration. In capillary systems, water moves according to water-potential gradients and crop demand; therefore, the planting medium must maintain a balance between water availability and air-filled pore space.

A2 tended to support better moisture stabilization than A1 because it had higher bulk density and lower total pore space. A denser medium can hold water longer and reduce rapid moisture decline due to evaporation. Razzaghi et al. (2020) reported that changes in soil physical properties, especially bulk density and water-retention characteristics, strongly influence plant-available water. Acharya et al. (2024) also noted that organic and porous amendments can modify soil structure, porosity, hydraulic conductivity, and water-storage dynamics. Thus, in floating sub-irrigation, the planting medium acts not only as a rooting substrate but also as a water-regulating component.

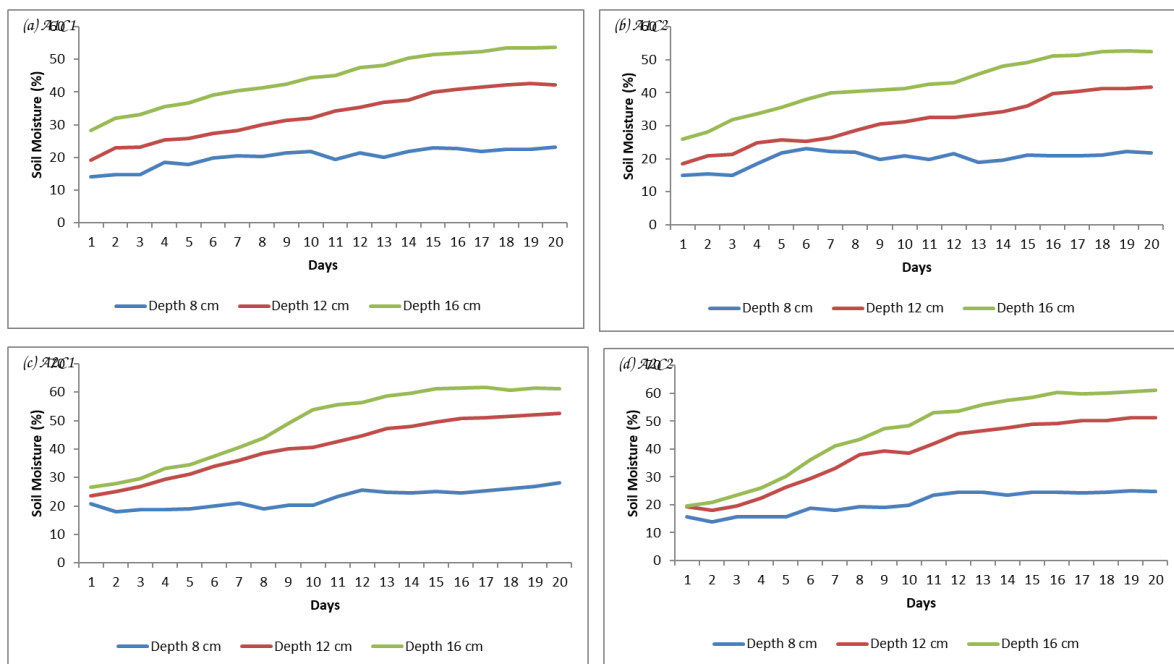


Figure 2. Root-zone moisture dynamics before transplanting under floating sub-irrigation: (a) A1C1, (b) A1C2, (c) A2C1, and (d) A2C2.

3.3. Root-zone moisture dynamics during vegetative growth

After transplanting, root-zone moisture dynamics were influenced by the interaction among capillary supply, media retention, surface evaporation, and crop water uptake. During the early vegetative stage, treatments with A2 maintained moisture better than treatments with A1. This result indicates that the soil-manure medium provided a physical condition more suitable for retaining water around the roots. Moisture stability was particularly important at this stage because the seedlings were still adapting after transplanting and the root system had not fully developed.

During the middle vegetative stage, crop water demand increased with canopy development and leaf production. At this stage, A2C1 provided the most favorable condition because it combined water retention in the planting medium with capillary supply from crushed tile particles. Such a condition supported a more stable root-zone environment. Moisture stability is important because excessive fluctuation can reduce cell expansion, restrict nutrient transport, and slow vegetative growth. In greenhouse vegetable systems, moisture monitoring and root-zone water regulation are key factors in maintaining productivity (Thompson et al., 2020).

During the late vegetative stage, treatments with more porous media or higher wick conductivity tended to experience greater moisture decline. This response was likely related to increased plant water uptake and evaporation from the upper layer. A1 had a higher total pore space and could distribute water rapidly, but its capacity to retain water was lower than A2. In contrast, A2C1 maintained a steadier supply of water, allowing the crop to meet its demand without creating excessively wet conditions. This confirms that floating sub-irrigation should be designed to stabilize root-zone moisture rather than merely to increase water-flow rate.

3.4. Plant height response

Plant height responded significantly to the combination of planting medium and suction medium. In the first week after transplanting, A2C1 reached 6.23 ± 0.50 cm and formed the highest statistical group, whereas A1C1, A1C2, and A2C2 were grouped together at lower values. At the fourth week, factorial ANOVA showed significant effects of planting medium ($p < 0.001$), suction medium ($p < 0.001$), and $A \times C$ interaction ($p = 0.0048$). A2C1 produced the highest numerical plant height at 22.17 ± 0.47 cm, but it was statistically comparable with A2C2 at 21.60 ± 0.78 cm. Both A2-based treatments were significantly higher than A1C1 (16.00 ± 0.64 cm) and A1C2 (12.83 ± 0.38 cm), indicating that the soil-manure medium improved final plant height under floating sub-irrigation.

The greater plant height under A2C1 indicates that the soil-manure medium combined with crushed tile suction created the most suitable water environment for pakchoi growth. Plant height is a vegetative-growth indicator influenced by water availability, nutrient transport, and root aeration. In sub-irrigation systems, water is supplied from below, allowing the root zone to receive water through capillary movement while reducing excessive wetting of the surface. Vahabi Mashhor et al. (2020) showed that sub-irrigated planter systems can improve crop performance because water supply is more controlled than in surface irrigation.

A1C2 produced the lowest plant height in the fourth week. This indicates that a highly porous planting medium combined with a high-conductivity fabric wick did not necessarily create the best root environment. Water may have moved relatively quickly, but it was not retained sufficiently in the upper root zone. Therefore, plant height was more strongly associated with the moisture stability maintained by the planting medium than with the water-transmission capacity of the suction medium alone.

Table 3. Plant height of pakchoi under floating sub-irrigation across four weeks after transplanting.

Treatment	Week 1	Week 2	Week 3	Week 4
A1C1	$4.27 \pm 0.48b$	$5.50 \pm 0.29c$	$9.60 \pm 0.26c$	$16.00 \pm 0.64b$
A1C2	$4.63 \pm 0.19b$	$5.87 \pm 0.27c$	$6.97 \pm 0.41d$	$12.83 \pm 0.38c$
A2C1	$6.23 \pm 0.50a$	$11.33 \pm 0.60a$	$15.17 \pm 0.17a$	$22.17 \pm 0.47a$
A2C2	$4.73 \pm 0.12b$	$8.43 \pm 0.35b$	$12.83 \pm 0.44b$	$21.60 \pm 0.78a$

Values are mean \pm SE ($n = 3$). Different lowercase letters within the same week indicate significant differences according to the LSD test at $p \leq 0.05$.

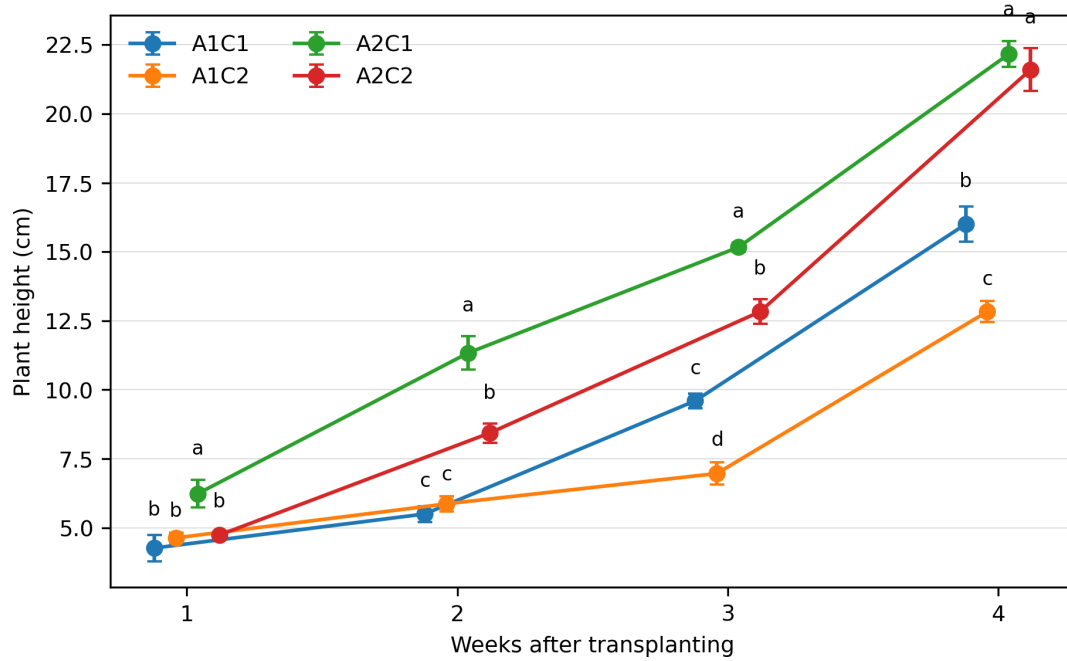


Figure 3. Plant height dynamics of pakchoi under floating sub-irrigation across 1-4 weeks after transplanting. Values are mean \pm SE ($n = 3$), and different lowercase letters within the same week indicate significant differences among treatments according to the LSD test at $p \leq 0.05$.

3.5. Leaf number response

The number of leaves showed a pattern consistent with plant height. In the first week, A2C1 produced the highest leaf number at 5.00 ± 0.58 leaves plant⁻¹ and was significantly higher than the other treatments. In the fourth week, factorial ANOVA showed a highly significant effect of planting medium ($p < 0.001$) and a significant effect of suction medium ($p = 0.0212$), whereas the $A \times C$ interaction was not significant ($p = 0.1723$). A2C1 (10.00 ± 0.00 leaves plant⁻¹) and A2C2 (9.67 ± 0.33 leaves plant⁻¹) formed the highest statistical group, followed by A1C1 (7.33 ± 0.33 leaves plant⁻¹) and A1C2 (6.33 ± 0.33 leaves plant⁻¹).

Leaf number is an important indicator for pakchoi because the edible and economically valuable component is the shoot canopy. Stable root-zone moisture supports turgor pressure, cell division, leaf expansion, and nutrient transport. Under A2C1, water availability was more balanced, supporting leaf formation throughout the vegetative stage. This agrees with the general principle that leafy vegetable productivity is sensitive to water availability during active vegetative growth.

The result also supports the global evidence summarized by Wang et al. (2022), who found that subsurface irrigation systems can improve yield and water productivity, although the magnitude of improvement depends on soil factors and system management. In the present study, differences in leaf number indicate that planting-medium characteristics played a dominant role in the effectiveness of capillary water supply. A2 provided a more favorable condition for leaf growth because it retained water more steadily than A1.

Table 4. Leaf number of pakchoi under floating sub-irrigation across four weeks after transplanting.

Treatment	Week 1	Week 2	Week 3	Week 4
A1C1	$2.00 \pm 0.00c$	$4.00 \pm 0.58b$	$5.00 \pm 0.00c$	$7.33 \pm 0.33b$
A1C2	$2.67 \pm 0.33c$	$3.67 \pm 0.33b$	$5.00 \pm 0.58c$	$6.33 \pm 0.33c$
A2C1	$5.00 \pm 0.58a$	$6.00 \pm 0.58a$	$7.67 \pm 0.33a$	$10.00 \pm 0.00a$
A2C2	$4.00 \pm 0.00b$	$5.67 \pm 0.33a$	$6.00 \pm 0.00b$	$9.67 \pm 0.33a$

Values are mean \pm SE ($n = 3$). Different lowercase letters within the same week indicate significant differences according to the LSD test at $p \leq 0.05$.

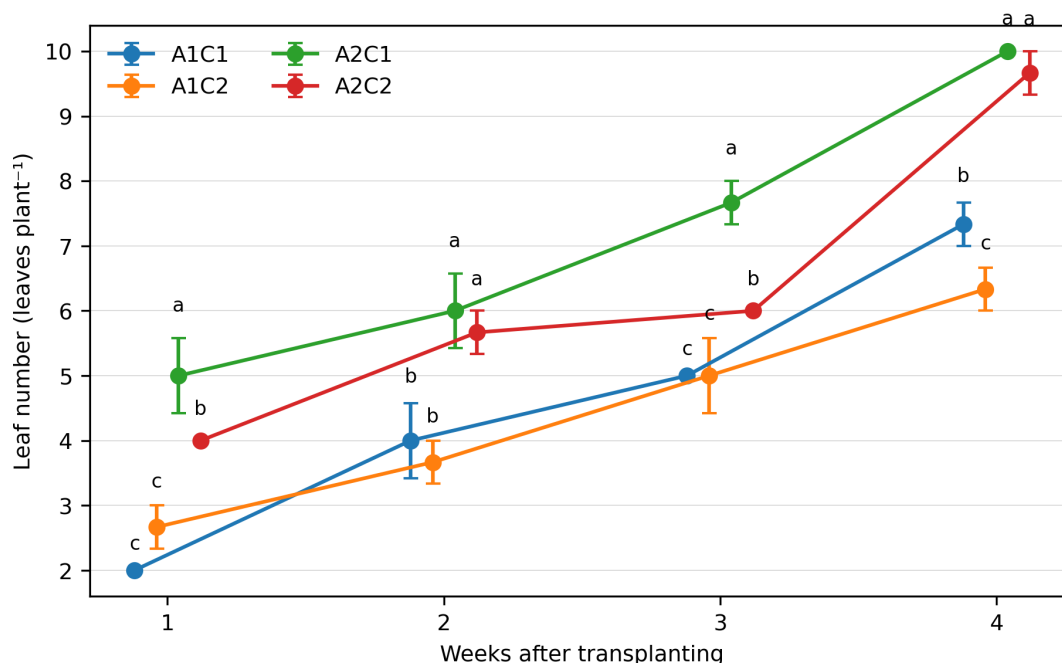


Figure 4. Leaf number dynamics of pakchoi under floating sub-irrigation across 1-4 weeks after transplanting. Values are mean \pm SE ($n = 3$), and different lowercase letters within the same week indicate significant differences among treatments according to the LSD test at $p \leq 0.05$.

3.6. Fresh biomass production

Fresh biomass provided statistical support for the superior performance of the A2 planting medium. Factorial ANOVA showed that fresh biomass was significantly affected by planting medium ($p = 0.0038$), whereas suction medium ($p = 0.7003$) and the $A \times C$ interaction ($p = 0.8793$) were not significant. A2C1 produced the highest numerical fresh biomass of $86.21 \pm 14.68 \text{ g plant}^{-1}$, followed by A2C2 at $80.35 \pm 17.82 \text{ g plant}^{-1}$, and both treatments belonged to the highest LSD group. A1C1 and A1C2 produced significantly lower fresh biomass, at 36.80 ± 1.60 and $34.24 \pm 0.75 \text{ g plant}^{-1}$, respectively. Therefore, the large biomass difference between A2C1 and the A1-based treatments is statistically supported, mainly through the significant planting-medium effect.

The superiority of A2C1 can be explained by the relationship between media hydraulics and plant response. A2 had lower hydraulic conductivity and higher bulk density, allowing water to remain available longer in the root zone. C1, as crushed tile suction medium, provided sufficiently stable capillary flow. This combination enabled continuous water availability without excessive moisture fluctuation. In contrast, A1 had higher total pore space and lower bulk density, making the medium more porous and less effective at retaining water around the roots.

These results demonstrate that fresh pakchoi biomass was not determined solely by the amount of water lifted from the reservoir, but by the match between water-supply rate and water-storage capacity. In leafy vegetables, fresh biomass is closely related to tissue water status and canopy development. When root-zone moisture is stable, plants can maintain turgor, expand leaves, and accumulate biomass. Semananda et al. (2018) noted that capillary irrigation can improve crop yield and reduce water use when the system maintains a water supply compatible with plant demand. Therefore, A2C1 can be considered the most suitable combination for pakchoi under floating sub-irrigation.

Table 5. Fresh biomass of pakchoi at harvest under floating sub-irrigation.

Treatment	Fresh biomass (g plant^{-1})
A1C1	$36.80 \pm 1.60\text{b}$
A1C2	$34.24 \pm 0.75\text{b}$
A2C1	$86.21 \pm 14.68\text{a}$
A2C2	$80.35 \pm 17.82\text{a}$

Values are mean \pm SE ($n = 3$). Different lowercase letters indicate significant differences according to the LSD test at $p \leq 0.05$.

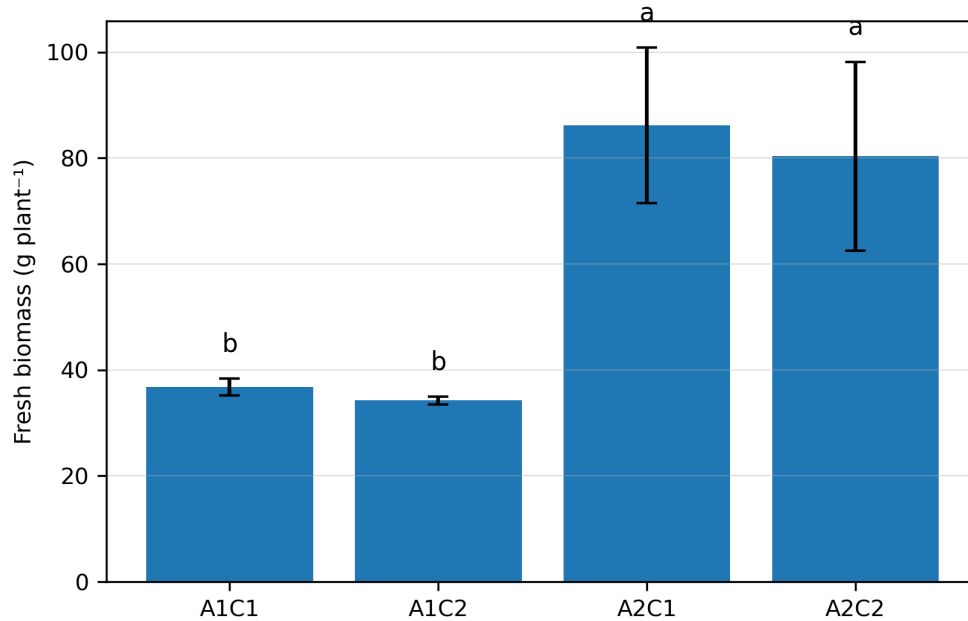


Figure 5. Fresh biomass of pakchoi at harvest under floating sub-irrigation. Values are mean \pm SE ($n = 3$), and different lowercase letters indicate significant differences among treatments according to the LSD test at $p \leq 0.05$.

3.7. Implications for floating sub-irrigation in wetland vegetable farming

The findings indicate that floating sub-irrigation has potential as an appropriate technology for vegetable cultivation in wetland areas. In inundated environments, the main problem is not only water availability but also how water can be regulated so that the root zone remains moist, stable, and sufficiently aerated. The system allows plants to grow on a floating platform while water from the reservoir or surrounding inundation is used through capillary movement.

This implication is relevant to Karmaker et al. (2023), who showed that floating agriculture can be an alternative cropping system under waterlogged conditions as a form of climate-change adaptation. Islam (2026) also emphasized that wetland agriculture requires adaptation strategies capable of reducing flood risk while maintaining production. In this context, floating sub-irrigation offers a more controlled approach than traditional floating cultivation because water delivery to the root zone can be regulated through the selection of planting and suction media.

Scientifically, the study shows that floating sub-irrigation design should be based on media hydraulics. The best medium combination was not the one with the fastest water transmission, but the one capable of balancing capillary flow, moisture retention, and crop water demand. Practically, the soil-manure medium combined with crushed tile particles can be recommended as an initial configuration for developing passive floating irrigation for pakchoi. Further testing under open-field wetland conditions, different seasons, and other vegetable crops is needed to support broader application.

4. CONCLUSION

The results showed that media hydraulics played an important role in controlling root-zone moisture dynamics, vegetative growth, and pakchoi yield under floating sub-irrigation. The soil-manure planting medium at a ratio of 3:1 (A2) had lower hydraulic conductivity ($4.23 \times 10^{-5} \text{ cm s}^{-1}$) and higher bulk density (0.97 g cm^{-3}) than the soil-rice husk charcoal-manure medium. These characteristics indicate that A2 retained water more effectively in the root zone and supported more stable moisture conditions during pakchoi growth.

The A2C1 treatment, consisting of soil-manure planting medium and crushed tile suction medium, produced the highest numerical crop response and belonged to the highest statistical group for final plant height, leaf number, and fresh biomass. This treatment resulted in plant height of $22.17 \pm 0.47 \text{ cm}$, leaf number of $10.00 \pm 0.00 \text{ leaves plant}^{-1}$, and fresh biomass of $86.21 \pm 14.68 \text{ g plant}^{-1}$. However, these final growth and biomass responses were statistically comparable with A2C2, indicating that the A2 planting medium was the dominant factor controlling crop performance. The result confirms that floating sub-irrigation performance is not determined only by the ability of the suction medium to transmit water rapidly, but mainly by the balance between capillary supply and the ability of the planting medium to retain root-zone moisture.

Overall, floating sub-irrigation can be developed as a passive, low-energy, and adaptive irrigation technology for vegetable cultivation in wetland areas. The scientific contribution of this study is the demonstration that floating

irrigation design should be based on media hydraulics, particularly the relationship among hydraulic conductivity, bulk density, root-zone moisture stability, and plant-growth response. A2C1 can be recommended as an initial configuration for pakchoi cultivation under floating sub-irrigation because it produced the highest numerical response and used a stable crushed-tile suction medium; nevertheless, future studies should compare A2C1 and A2C2 under open-field wetland conditions, different planting seasons, and other vegetable crops to validate agronomic effectiveness and practical scalability.

Because the experiment was based on archived 2015 greenhouse data, the findings should be interpreted as controlled-condition evidence and require field validation under current wetland production environments. In addition, the relatively small number of replications ($n = 3$ per treatment) and the correspondingly wide standard errors observed for fresh biomass limit the generalization of the findings; therefore, larger-scale validation is needed before broader application.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY

Data are available from the corresponding author upon reasonable request.

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