

Growing Media Affects Biomass-Water Use Efficiency Trade-Off in Sub-Surface Irrigated Pak Choi (*Brassica rapa* L. subsp. *chinensis*)

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Efficient water use is crucial for the sustainable production of leafy vegetables under limited water resources. This study evaluated the trade-off between biomass production and water use efficiency (WUE) in pak choi (*Brassica rapa* L. subsp. *chinensis*) grown under a sub-surface capillary irrigation system across three growing media: rice husk charcoal (RHC), sand (SPM), and cocopeat (CPT). A completely randomised design with three replications was used over a 24-day growth period. Results showed that while CPT produced the highest total biomass (108.8 g/plant) and canopy area (472.8 cm²), these vegetative parameters were not significantly different across media ($p > 0.05$). In contrast, water relations varied significantly; SPM achieved the highest water productivity (87.8 kg/m³), representing a 34.4% improvement over CPT ($p < 0.05$). Root biomass and length also varied significantly among media. No significant linear correlation was found between vapour pressure deficit (VPD) and daily evapotranspiration (ET_c) for any growing medium ($|r| \leq 0.101$, $p > 0.05$). These findings highlight a trade-off between biomass yield and water efficiency. For water-limited systems, SPM is recommended; for balanced performance, RHC is suitable. The hypothesis that a mixture of CPT and SPM could optimise both biomass yield and water conservation requires direct testing in future studies.

Key words: cocopeat, sand, rice husk charcoal, sub-surface irrigation, pak choi, water use efficiency, biomass production

Water scarcity is a major constraint on sustainable agricultural production in the 21st century. Agriculture accounts for approximately 70% of global freshwater withdrawals, and increasing competition from urban and industrial sectors further intensifies water stress in many regions (FAO 2020). A significant share of this agricultural water is returned to the atmosphere through evapotranspiration (ET), a complex process that combines water evaporation from the soil surface and transpiration from the plant canopy. As global temperatures rise and climate patterns shift, atmospheric evaporative demand is intensifying, rapidly accelerating ET rates and exacerbating water deficits in cultivated areas.

Consequently, understanding and managing ET dynamics has become an urgent global priority. Because non-productive soil evaporation represents a direct and substantial water loss, modern agricultural strategies must focus on minimising this component while optimising beneficial plant transpiration. Improving water use efficiency (WUE) is therefore essential to achieve sustainable agricultural intensification (Lakhari *et al.* 2024).

Pak choi (*Brassica rapa* L. subsp. *chinensis*) is a fast-growing leafy vegetable widely cultivated in Southeast Asia for its high commercial value and strong consumer demand. Economically, its short growth cycle enables multiple harvests per year,

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providing a rapid, continuous income for farmers and helping stabilise the vegetable supply across traditional and modern agricultural systems (Sim *et al.* 2025). Furthermore, pak choi offers substantial health benefits; it is low in calories yet rich in essential vitamins (A, C and K), minerals, dietary fibre, and bioactive compounds such as glucosinolates and flavonoids, which are driving its growing global market demand (Wang *et al.* 2023; Kim *et al.* 2024). Despite its economic and nutritional importance, pak choi has high water requirements during vegetative growth and a shallow root system that limits access to deep soil moisture. Conventional irrigation methods, such as surface or overhead sprinkler irrigation, often result in substantial water losses through evaporation, deep percolation, and runoff, typically achieving less than 60% application efficiency (González-Trinidad *et al.* 2020; Lakhari *et al.* 2024). These losses not only reduce WUE but also increase nutrient leaching and the risk of environmental contamination.

Sub-surface irrigation systems, particularly those based on capillary mats, offer a promising approach to precise water delivery in modern agriculture. Water is supplied directly to the root zone from below via capillary action. Unlike traditional overhead watering, this method significantly reduces the wetted surface area of the topsoil, thereby minimising evaporative losses and maintaining a highly uniform root-zone moisture profile. However, the effectiveness of such systems depends largely on the physical properties of the growing media, specifically their bulk density, pore-size distribution, and capillary rise capacity, which determine water retention, aeration, and root development. Hence, understanding the interaction between growing media characteristics and sub-surface irrigation mechanisms is essential for optimising overall system performance and ensuring that water reaches the active root zone efficiently.

Cocopeat, sand and rice husk charcoal are commonly used as growing media, each with distinct hydraulic characteristics and varying degrees of sustainability. Cocopeat, a widely available organic by-product, has high porosity and exceptional water-holding capacity, supporting rapid plant growth but often leading to higher water consumption due to continuous evaporation from its highly saturat-

ed micropores. Sand provides good drainage and moderate moisture retention, potentially improving WUE under limited water conditions, though its low nutrient-retention capacity may require more precise fertigation management. Rice husk charcoal, another abundant agricultural waste, combines good aeration with variable water retention, offering performance intermediate between the two while also contributing to carbon sequestration and improved root aeration. Selecting the appropriate medium is therefore a critical step in maximising the efficiency of capillary-driven irrigation.

Atmospheric demand, expressed as vapour pressure deficit (VPD), also plays an important role in determining plant transpiration and water use (Grossiord *et al.* 2020). Under high VPD, plants often experience increased transpiration, which can trigger stomatal closure, reduce photosynthesis, and ultimately lower biomass production if the root system cannot extract sufficient water from the substrate. However, few studies have examined how the continuous, stable water supply provided by sub-surface irrigation may reduce dependence of plant water uptake on VPD, especially for leafy vegetables grown in different growing media. If a specific medium can maintain optimal hydraulic conductivity under capillary irrigation, it could buffer plants against VPD-induced water stress. This research gap highlights the need to integrate plant–atmosphere interactions with irrigation system evaluation to improve understanding of water dynamics in controlled environments.

Previous studies have primarily examined irrigation technologies or growing media separately. Consequently, the combined effects of irrigation method and growing medium on the trade-off between biomass production and WUE remain poorly understood. Moreover, most existing research has focused on fruiting vegetables, such as tomatoes and cucumbers (Nikolaou *et al.* 2021; Agbemabiese *et al.* 2023), whereas leafy crops such as pak choi – with distinct physiological and water-use characteristics – have received less attention.

Therefore, the objectives of this study were to: (1) quantify pak choi biomass production under sub-surface capillary irrigation across different growing media; (2) evaluate WUE across media types; (3) analyse the relationship between VPD and

plant water consumption; and (4) develop media selection criteria to optimise biomass production and water conservation. Ultimately, the findings provide practical engineering parameters for designing and operating efficient sub-surface irrigation systems. By utilising these results, growers and agricultural engineers can directly select the most appropriate growing media to maximise leafy vegetable yields while significantly reducing agricultural water waste in water-limited environments.

MATERIAL AND METHODS

Experimental Site and Duration

The experiment was conducted from February to March 2025 in a naturally ventilated greenhouse at the Department of Agricultural and Biosystem Engineering, Faculty of Agriculture, University of Lampung, Bandar Lampung, Indonesia. This period coincided with the seasonal transition, providing a range of microclimatic conditions (specifically varying intensities of solar radiation and vapour pressure deficit) suitable for evaluating the water-use dynamics of the sub-surface irrigation system under fluctuating atmospheric demands. The greenhouse measured 2.0 m (width) × 4.0 m (length) × 2.5 m (height), with a UV-protected plastic roof and netted sidewalls. No active environmental control was applied; internal microclimatic conditions were regulated solely by natural ventilation.

Plant Material and Growing Media

Certified pak choi (*Brassica rapa* L. subsp. *chinensis*) seeds were used. Three growing media were tested: (1) rice husk charcoal (RHC), (2) sand pasir malang (SPM), and (3) cocopeat (CPT). All media were sterilised at 80°C for 30 minutes before use to eliminate potential pathogens.

Seeds were initially sown in 3 cm × 3 cm rock-wool plugs. Uniform seedlings at the 3–4-leaf stage (14 days after sowing, DAS) were transplanted into Styrofoam boxes (37.5 cm × 24.0 cm × 16.0 cm) containing an 11 cm layer of the respective growing medium. A polyester flannel layer was placed at the bottom of each box to serve as a capillary mat, facilitating upward water movement from a reservoir into the substrate (Figure 1 a, b).

Experimental Design

A completely randomised design (CRD) was used with three treatments (RHC SPM CPT) and three replicates, yielding a total of nine experimental units. Each experimental unit contained four plants treated as subsamples; measurements from the four plants were averaged per container prior to statistical analysis to ensure statistical independence, resulting in 36 plants being monitored throughout the study.

Sub-surface Irrigation System Setup

The sub-surface capillary mat system comprised: an 8-L water reservoir, a 3-mm-thick polyester capillary mat with a 10-cm water-rise capacity, and Styrofoam boxes (37.5 cm × 24.0 cm × 16.0 cm) filled with an 11-cm layer of the respective growing medium. The water level was maintained 5 cm below the container base, allowing water to rise via capillary action.

Crop Establishment and Management

Seedlings were transplanted at four plants per container. Nutrient solution (AB Mix, TDS 1,000–1,400 ppm, pH 6.0) was delivered through the irrigation system. Pest and disease management followed integrated pest management principles; no chemical pesticides were applied.

Data Collection and Analysis

Microclimate Parameters: Air temperature [°C] and relative humidity [%] were recorded hourly at canopy height within the greenhouse using data loggers. Vapour pressure deficit (VPD) was calculated using Equation (1).

$$VPD = 0.6108 \times \exp\left(\frac{17.27 \times T}{T + 237.3}\right) \times \left(1 - \frac{RH}{100}\right) \quad (1)$$

where: T is air temperature [°C] and RH is relative humidity [%].

Over the 24-day experimental period, the daily average temperature ranged from 27.0°C to 34.8°C, relative humidity from 55.5% to 83.5%, and VPD from 0.6 kPa to 2.5 kPa, providing a wide range of atmospheric conditions suitable for evaluating irrigation system performance under fluctuating evaporative demand. A summary of microclimatic conditions is presented in Table 1.

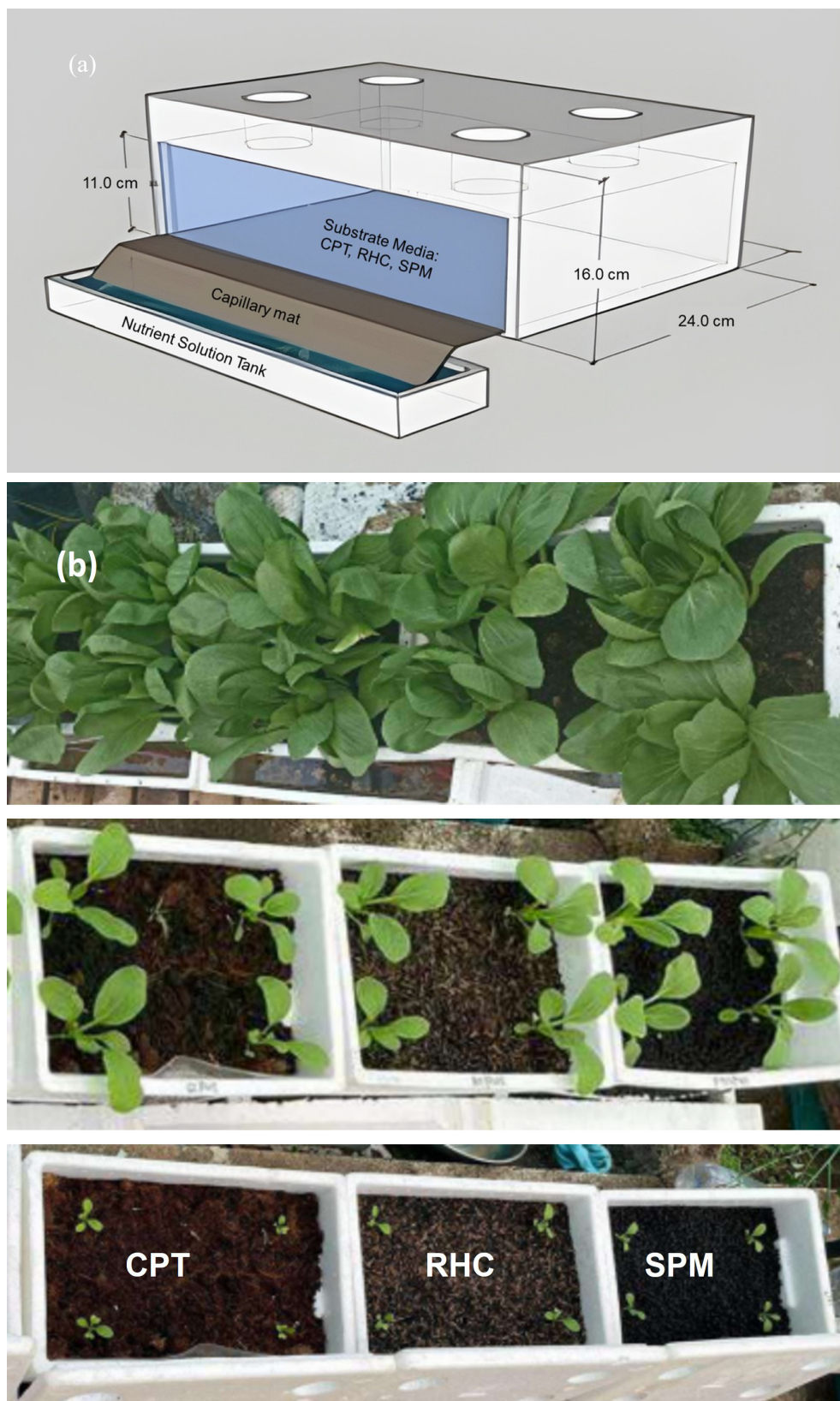


Figure 1. (a) Cultivation setup showing Styrofoam boxes with capillary mat; and (b) representative pak choi plants at 24 DAT (harvest time). Actual plant height at harvest ranged from 21.8 cm to 23.7 cm depending on treatment (see Table 2).
Note: RHC – rice husk charcoal; SPM – sand pasir malang; CPT – cocopeat; DAT – days after transplanting

T a b l e 1

Summary of microclimatic conditions inside the greenhouse during the experimental period
(24 days, February–March 2025)

Parameter	Mean $\pm$ SD	Minimum	Maximum
Air temperature [°C]	30.30 $\pm$ 2.00	27.00	34.80
Relative humidity [%]	70.60 $\pm$ 8.00	55.50	83.50
Vapour pressure deficit [kPa]	1.30 $\pm$ 0.50	0.60	2.50

Note: VPD was calculated from hourly temperature and RH data, then averaged daily. Values are daily averages $\pm$ standard deviation, with minimum and maximum ranges.

Actual Evapotranspiration and Water Consumption: The actual crop evapotranspiration (ET_c) was determined daily using a volumetric water balance approach. The daily water input required to maintain the reservoir at its predetermined level was accurately recorded.

Because the sub-surface capillary system was designed as a closed system (Figure 1a), losses due to deep percolation (D) and surface runoff (R) were negligible (D=0 and R=0). Thus, the daily ET_c is equivalent to the volume of water replenished to the reservoir (V_{replenished}) required to maintain a constant water level:

$$ET_{c, \text{ daily}} = V_{\text{replenished}, i} \quad (2)$$

The total water consumed (W_{total} , L) over the 24-day growth period was calculated as the cumulative sum of daily replenishments:

$$W_{\text{total}} = \sum_{i=1}^n ET_{c, \text{ daily}} \quad (3)$$

Subsequently, water use efficiency (WUE), referred to in this study as water productivity (WP, kg/m³), was calculated as the ratio of fresh biomass produced (B_{fresh}, g) to the total volume of water consumed (W_{total} , L), as follows:

$$WP = \frac{B_{\text{fresh}} \text{ (g)}}{W_{\text{total}} \text{ (L)}} \times 1000 \quad (4)$$

Note: A conversion factor was applied to express the final result in kg/m³.

This direct measurement method ensures that the WP values accurately reflect the true efficiency of the sub-surface system in converting consumed water into plant biomass across the different growing media.

Growth Parameters: At harvest (24 DAT), a time point selected because the plants had reached the optimal commercial size for young pak choi, driven by the accelerated growth rates typical of optimised sub-surface capillary systems, the following parameters were measured:

- Plant height [cm]: measured from the substrate base to the highest leaf tip.
- Canopy area [cm²]: calculated as the product of two perpendicular diameter measurements.
- Total fresh weight [g]: representing the total above-ground biomass.
- Root fresh weight [g] and length [cm]: measured after careful extraction and washing of the root system to remove substrate particles.

Statistical Data Analysis: Data were analysed in R version 4.2.1. One-way ANOVA was used to test treatment effects. Significant differences ($p < 0.05$) were further assessed using Tukey's HSD for mean separation. Pearson correlation was used to assess the relationship between VPD and water consumption. All procedures adhered to standard protocols for greenhouse crop experiments, with appropriate quality control measures throughout the study.

RESULTS AND DISCUSSION

Trade-off Between Biomass Production and Water Use Efficiency

The study revealed a trade-off between biomass production and water use efficiency (WUE) mediated by substrate characteristics (Table 2). Although ccopeat (CPT) produced the highest total biomass (108.75 g/plant), Tukey's HSD test indicated no sig-

T a b l e 2

Biomass production, water use, and root development of pak choi under three growing media (RHC SPM CPT).
Values are means $\pm$ standard deviation

Parameter	RHC	SPM	CPT	<i>F</i> -value	<i>p</i> -value
Biomass Production					
Total biomass [g/plant]	85.92 $\pm$ 4.30 ^a	104.42 $\pm$ 3.80 ^a	108.75 $\pm$ 5.10 ^a	3.124	0.098
Plant height [cm]	21.83 $\pm$ 1.15 ^a	23.58 $\pm$ 1.52 ^a	23.67 $\pm$ 2.13 ^a	2.347	0.187
Canopy area [cm ²]	405.50 $\pm$ 37.60 ^a	486.63 $\pm$ 86.10 ^a	472.76 $\pm$ 54.90 ^a	1.625	0.256
Water Relations					
Water consumption [L/plant]	1.261 $\pm$ 0.02 ^b	1.190 $\pm$ 0.01 ^c	1.666 $\pm$ 0.03 ^a	112.45	<0.001
Water productivity [kg/m ³]	68.11 $\pm$ 1.2 ^b	87.75 $\pm$ 1.5 ^a	65.28 $\pm$ 1.1 ^b	189.45	<0.001
Root Development					
Root biomass [g]	9.17 $\pm$ 1.01 ^a	6.42 $\pm$ 1.00 ^b	10.75 $\pm$ 1.38 ^a	8.912	0.008
Root length [cm]	17.33 $\pm$ 0.64 ^a	13.79 $\pm$ 2.01 ^b	15.03 $\pm$ 1.93 ^{ab}	5.782	0.034

Note: RHC – rice husk charcoal; SPM – sand pasir malang, CPT – cocopeat. Values are means standard deviation ($n = 3$ replications per treatment). Different letters within rows indicate significant differences among growing media according to Tukey's HSD test at $p < 0.05$. *F*-values and *p*-values are from one-way ANOVA, indicating the significance of the growing-medium effect.

nificant difference in biomass production among the three media ($p = 0.098$), suggesting that all substrates were equally capable of supporting pak choi growth under the capillary irrigation system. However, water relations showed highly significant variation. Based on the HSD test, CPT, RHC and SPM were all significantly different from each other in terms of water consumption ($p < 0.001$), with CPT consuming the most (1.666 L/plant) and SPM the least (1.190 L/plant). Consequently, SPM achieved a significantly higher water productivity (87.75 kg/m³), representing a 34.4% improvement over CPT and a 28.6% reduction in cumulative water consumption. This provides a practical framework for growers: prioritise water efficiency using SPM under limited water availability without a statistically significant loss in biomass.

Vegetative growth parameters (plant height and canopy area) did not differ significantly across media ($p > 0.05$), indicating that all substrates supported adequate above-ground development. Significant differences in root traits and water-use parameters suggest that variations in WUE primarily arise from hydrological properties and root architecture rather than from nutrient availability.

Root Architecture and Water Use Efficiency

Root architecture helps explain the physiological mechanisms underlying the contrasting water-use patterns observed in this study (Figure 2). As illustrated in Figure 2a, different growing media induced distinct root morphological traits. CPT promoted extensive root biomass (10.75 g), whereas RHC produced the longest root system (17.3 cm). In contrast, SPM produced significantly smaller and shorter root systems (6.42 g). Cocopeat tends to promote more extensive root development due to its high water-holding capacity (WHC) and fibrous structure, whereas sand – with low WHC and high drainage – produces smaller root systems but may exhibit greater resource uptake efficiency per unit of root mass (Ajelouni *et al.* 2024; Nair *et al.* 2024).

The relationship between root investment and water productivity is further illustrated in Figure 2b. A negative correlation was observed between root biomass and water productivity ($r = -0.97$). However, this trend was not statistically significant ($p = 0.162$), likely due to the limited number of media types compared ($n = 3$). Therefore, this trend should be interpreted with caution. Media that support compact root systems (such as SPM) may favour higher efficiency per unit biomass, but further studies with

a wider range of media are needed to confirm this relationship. Similar observations were reported by Lynch (2018) and Müllers *et al.* (2022), emphasising that reduced root proliferation in well-aerated, coarse media can improve hydraulic efficiency under controlled irrigation.

This pattern aligns with the Optimal Partitioning Theory, which posits that plants allocate biomass to organs that maximise the acquisition of the most limiting resource (Bloom *et al.* 1985). In the capillary system, where water is consistently supplied from below, the excessive root proliferation observed in

CPT did not translate into higher biomass production but instead increased total water consumption. This suggests that, for sub-surface irrigation, media that favour moderate, high-efficiency root systems (such as SPM) are preferable for optimising water-use efficiency.

Temporal Water Consumption Dynamics

Daily evapotranspiration (ET_c) varied over time (Figure 3b). As shown in Figures 3a and 3b, daily ET_c fluctuated, with the magnitude of these fluctuations differing across treatments. CPT recorded the

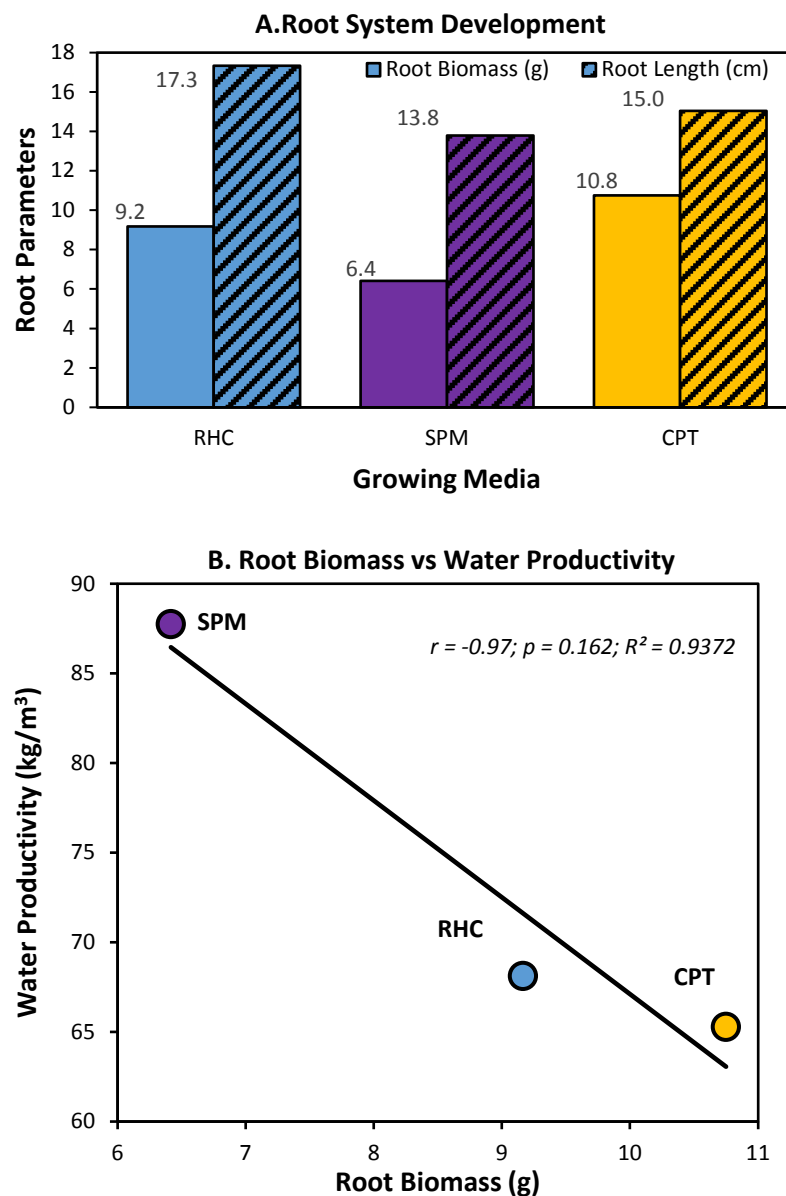


Figure 2. Root system traits of pak choi (*Brassica rapa* L. subsp *chinensis*) under different growing media: (A) comparative root biomass and length; (B) correlation between root traits and water productivity (WP).

Note: RHC – rice husk charcoal; SPM – sand pasir malang; CPT – coopeat.

highest daily ET_c on most days, with pronounced peaks that led to rapid divergence in cumulative water use compared with the other media (Figure 3c). Conversely, SPM maintained a relatively stable, lower ET_c profile. RHC provided intermediate responses, balancing water retention and aeration.

Cumulative water use confirmed that SPM was the most water-conservative (1,190 mL), RHC intermediate (1,261 mL), and CPT the highest (1,666 mL). These differences correspond to 29% water savings for SPM relative to CPT and 6% relative to RHC. SPM exhibited the most attenuated ET_c profile, maintaining relatively stable, low ET_c rates.

This conservative pattern, which resulted in the lowest cumulative water use (Figure 3c), likely stems from its coarse texture and limited water-holding capacity. Similar trends have been reported in container and green-roof studies, where sandy or coarse substrates reduce overall evapotranspiration due to faster drainage and lower surface moisture availability (Kader *et al.* 2022; Cuadrado-Alarcón *et al.* 2024). The large particle size creates a substrate dominated by macro-pores that retain less plant-available water, thereby restricting transpiration rates (Blok *et al.* 2021).

CPT consistently recorded the highest daily ET_c

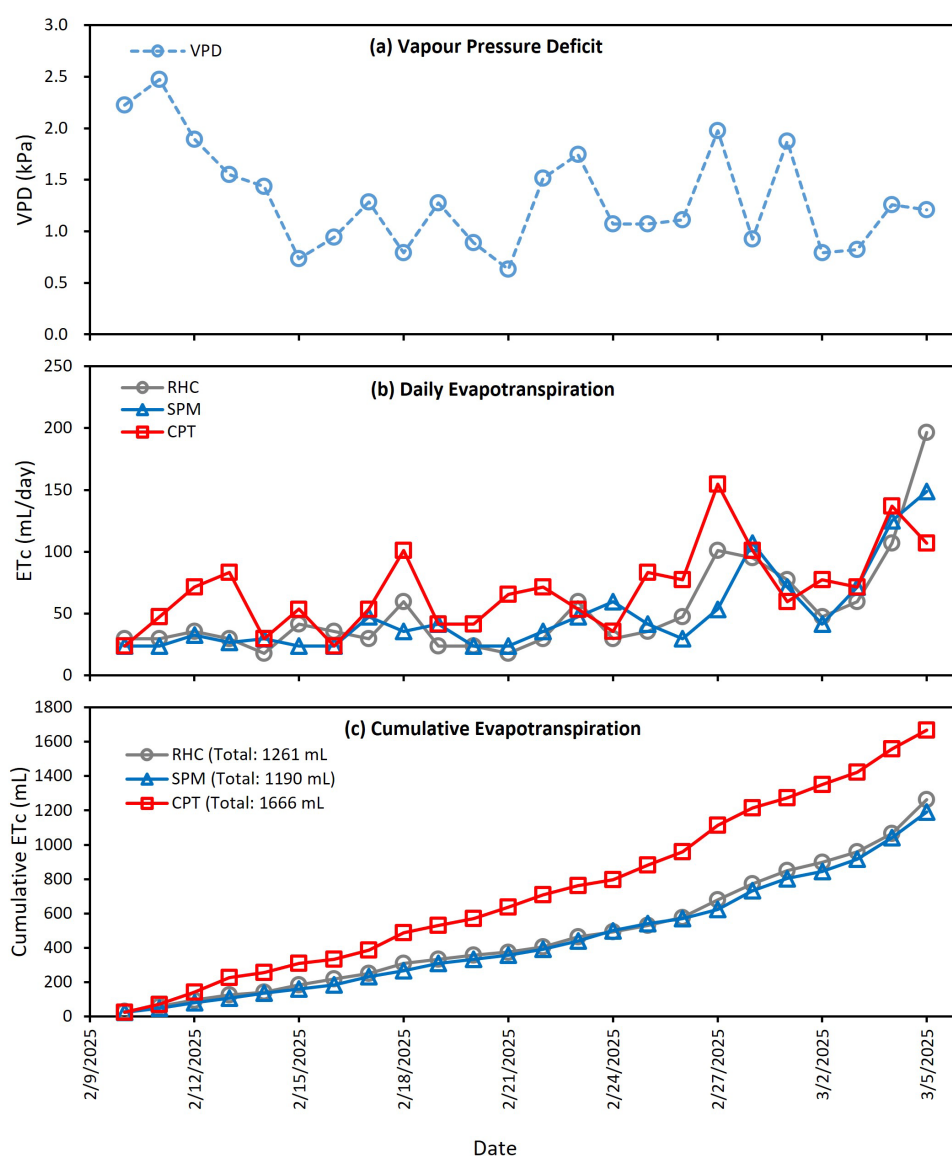


Figure 3. Water consumption dynamics under sub-surface capillary irrigation: (a) vapour pressure deficit (VPD); (b) daily evapotranspiration (ET_c); (c) cumulative evapotranspiration (ET_c, L/plant) for each growing medium.

Note: RHC – rice husk charcoal; SPM – sand pasir malang; CPT – cocopeat.

throughout the study, resulting in a significant divergence in cumulative water consumption compared with the other media. This response is attributable to cocopeat's high water-holding capacity and fine, fibrous structure, which provide a continuous, abundant supply of readily available water to the root zone (Martins *et al.* 2023). Furthermore, sustained water availability in CPT likely supported rapid canopy expansion, thereby increasing the total transpiration surface area. However, the high moisture retention of cocopeat can reduce air-filled porosity if not properly managed (e.g., by mixing with perlite or other coarse components), potentially compromising root aeration and lowering water-use efficiency (Barrett *et al.* 2016).

RHC exhibited an intermediate hydrological response, bridging the conservative behaviour of coarse SPM and the highly responsive CPT. The microporous structure of biochar increases water retention relative to coarse sandy media and generally improves bulk porosity and aeration compared with dense, fine organic media such as cocopeat. Consequently, RHC enabled moderate increases in ET_c during high-VPD periods – avoiding the extreme peaks seen with CPT while providing more reliable moisture availability than SPM – and resulted in substantially better overall water conservation than CPT under our experimental conditions (see Figure 3c).

Relationship Between Atmospheric Demand and Water Consumption

The correlation analysis (Table 3) found no significant linear relationship between daily vapour pressure deficit (VPD) and daily ET_c across any

growing medium ($|r| \leq 0.101$, $p > 0.05$ for all media). This contrasts with many conventional irrigation systems, where ET_c typically shows a positive correlation with VPD (Katsoulas *et al.* 2015). The absence of a significant correlation in our study suggests that the capillary mat irrigation system maintained stable root-zone moisture availability, potentially buffering short-term fluctuations in atmospheric demand. However, because root-zone water potential was not directly measured, this interpretation remains provisional. Importantly, the non-significant correlations do not support claims that one medium “decouples” water uptake more than another. The small differences in correlation coefficients ($r = -0.001$ to -0.101) were not tested for statistical significance and are likely within measurement variability. Therefore, we conclude that, under the conditions of this experiment, substrate type did not measurably alter the already weak relationship between VPD and ET_c.

SPM's consistent water use pattern, despite variable VPD conditions, further highlights its reliability for predictable irrigation management. This stability is particularly valuable in regions with high climatic variability, where traditional irrigation systems often struggle to maintain optimal soil moisture conditions.

Implications for Substrate Selection and Sustainable Production

The choice of substrate is a critical determinant of irrigation demand. For water conservation objectives, SPM is the most effective medium, as shown by its lowest cumulative ET_c in Figure 3c. RHC is a sustainable alternative that offers a very

T a b l e 3

Pearson correlation coefficients between vapour pressure deficit (VPD) and daily evapotranspiration (ET_c) for each growing medium

Growing Media	Correlation (r)	p-value	R ²
Rice Husk Charcoal (RHC)	-0.001	0.497	0.000
Sand Pasir Malang (SPM)	-0.101	0.322	0.010
Cocopeat (CPT)	-0.050	0.410	0.003

Note: r – Pearson correlation coefficients; R² – coefficient of determination; The p-values indicate the statistical significance of the linear relationship ($p < 0.05$ considered significant). For all media, $p > 0.05$, indicating no statistically significant correlation between VPD and ET_c.

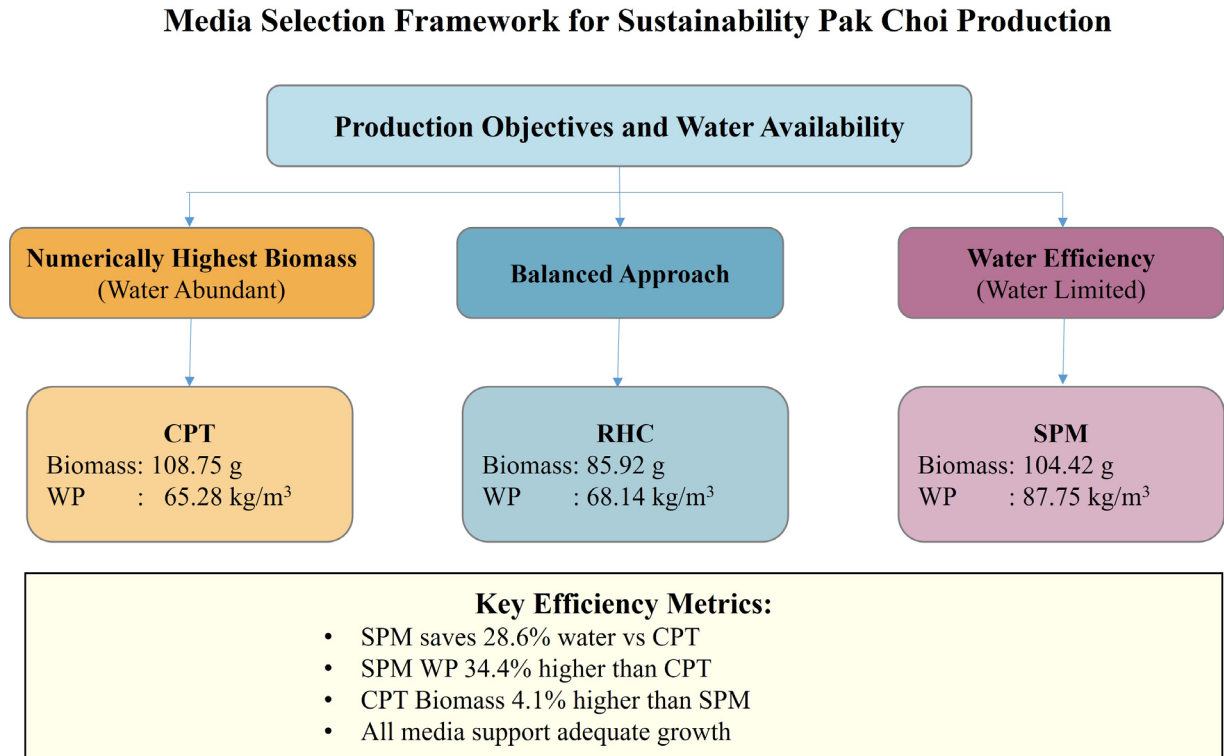


Figure 4. Preliminary decision framework for growing media selection in pak choy cultivation, integrating biomass production, water use efficiency, and water availability considerations.

Note: RHC – rice husk charcoal; SPM – sand pasir malang; CPT – cocopeat; WP – water productivity. Note that differences in biomass production among the growing media were not statistically significant ($p > 0.05$); CPT is recommended solely based on achieving the numerically highest biomass value.

slight increase in water use for potentially improved plant-available water, striking an excellent balance. CPT, while ensuring high water availability, requires substantially greater irrigation input.

Based on our findings, we propose a preliminary decision framework for media selection (Figure 4). In water-abundant environments, cocopeat is recommended to maximise yield. In water-limited regions or sustainable production systems, sand provides optimal water conservation with minimal compromise to yield. Rice husk charcoal serves as a balanced compromise for situations requiring trade-offs between competing objectives.

The dual advantage of sand – 28.6% water saving and 34.4% higher water productivity – represents a notable improvement in resource efficiency for sustainable agriculture. This translates into potential practical guidance for larger-scale operations aiming for resource conservation while maintaining competitive productivity, thereby addressing both economic viability and environmental sustainability (Steduto *et al.* 2012). Recent studies further rein-

force this notion, showing that precision and sub-surface irrigation systems can significantly enhance water-use efficiency and profitability by minimising evaporative and drainage losses while sustaining yields. Such findings highlight the role of efficient irrigation strategies in achieving sustainable intensification under limited water resources.

CONCLUSIONS

This study evaluated the trade-off between biomass production and water-use efficiency (WUE) in pak choy (*Brassica rapa* L. subsp. *chinensis*) grown under sub-surface capillary irrigation across three growing media: rice husk charcoal (RHC), sand pasir malang (SPM), and cocopeat (CPT). Based on the experimental results and corresponding to each objective:

- Biomass production: Biomass production (total fresh weight, plant height, and canopy area) did not differ significantly among the three grow-

ing media ($p > 0.05$). Although CPT produced the highest biomass (108.75 g/plant), all media supported adequate vegetative growth under the capillary irrigation system.

- Water use efficiency: Water relations varied significantly among media ($p < 0.001$). SPM achieved the highest water productivity (87.75 kg/m³), representing a 34.4% improvement over CPT, while consuming 28.6% less water (1.190 L/plant) compared to CPT (1.666 L/plant). RHC showed intermediate performance.
- VPD and water consumption: No significant linear correlation was observed between daily vapour pressure deficit (VPD) and daily evapotranspiration (ET_c) across any growing medium ($|r| \leq 0.101$, $p > 0.05$). This indicates that, under the capillary irrigation system, atmospheric demand did not act as a measurable driver of daily water consumption in this experiment.
- Media selection criteria: In water-limited environments, SPM is recommended as the most water-efficient medium. For a balance between growth and efficiency, RHC offers a suitable compromise. The hypothesis that a mixture of CPT and SPM could optimise biomass yield and water conservation requires direct testing in future studies.
- Practical implications: These findings provide practical engineering parameters for designing and operating sub-surface irrigation systems. Growers and agricultural engineers can directly select SPM to maximise water productivity or RHC for balanced performance, thereby reducing agricultural water waste in water-limited environments. However, as this was a single-season greenhouse experiment with three media and three replicates, further studies under different climatic conditions and with additional media types are needed to generalise these results.

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REFERENCES

- Agbemabiese, Y.K., Abubakari, A.H., Dzomeku, I.K., and Abdul-Ganiyu, S. (2023). Water and nutrient use efficiency of soilless grown greenhouse tomato (*Lycopersicon esculentum* L.). *Cogent Food and Agriculture*, 9(2). DOI:10.1080/23311932.2023.2275415.
- Al-Ajlouni, M.G., Othman, Y.A., Abu-Shanab, N.S., and Alzyoud, L.F. (2024). Evaluating the performance of cocopeat and volcanic tuff in soilless cultivation of roses. *Plants*, 13(16). DOI:10.3390/plants13162293.
- Arenas-Montaña, V., Fenton, O., Moore, B., and Healy M.G. (2021). Evaluation of the fertiliser replacement value of phosphorus-saturated filter media. *Journal of Cleaner Production*, 291. DOI:10.1016/j.jclepro.2021.125943.
- Barrett, G.E., Alexander, P.D., Robinson, J.S., and Bragg, N.C. (2016). Achieving environmentally sustainable growing media for soilless plant cultivation systems – A review. *Scientia Horticulturae*, 212, 220–234. DOI:10.1016/j.scienta.2016.09.030.
- Blok, C., Eveleens, B. and van Winkel A. (2021). Growing media for food and quality of life in the period 2020–2050. *Acta Horticulturae*, 1305, 341–355. DOI:10.17660/Acta-Hortic.2021.1305.46.
- Bloom, A.J., Chapin, F.S. and Mooney, H.A. (1985). Resource limitation in plants – an economic analogy. *Annual Review of Ecology and Systematics*, 16, 363–392. DOI:10.1146/annurev.ecolsys.16.110185.002051.
- Cuadrado-Alarcón, B., Vanwalleghe, T., Laguna, A.M., Hayas, A., Peña, A., Martínez, G., Lora, A., and Giraldez, J.V. (2024). Hydraulic property estimation of green roof substrates from soil moisture time series. *Water*, 16(19). DOI:10.3390/w16192716.
- FAO (2020). *The State of Food and Agriculture 2020. Overcoming water challenges in agriculture*. Rome: FAO. Available at: <https://doi.org/10.4060/cb1447en>.
- González-Trinidad, J., Jénez-Ferreira, H.E., Bautista-Capetillo, C., Dávila, L.Á., and Rovelo, C.O.R. (2020). Improving the water-use efficiency and the agricultural productivity: An application case in a modernized semiarid region in North-Central Mexico. *Sustainability*, 12(19). DOI:10.3390/su12198122.
- Grossiord, C., Buckley, T.N., Cernusak, L.A., Novick, K.A., Poulter, B., Siegwolf, R.T.W., Sperry, J.S., and McDowell, N.G. (2020). Plant responses to rising vapor pressure deficit. *New Phytologist*, 226(6), 1550–1566. DOI:10.1111/nph.16485.
- Guo, J., Zheng, L., Ma, J., Li, X., and Chen, R. (2023). Meta-analysis of the effect of subsurface irrigation on crop yield and water productivity. *Sustainability*, 15(22). DOI:10.3390/su152215716.
- Jani, A.D., Meadows, T.D., Eckman, M.A., and Ferrarezi, R.S. (2021). Automated ebb-and-flow subirrigation conserves water and enhances citrus liner growth compared to capillary mat and overhead irrigation methods. *Agricultural Water Management*, 246, 106711. DOI:10.1016/j.agwat.2020.106711.
- Kader, S., Chadalavada, S., Jauffer, L., Spalevic, V., and Dudić, B. (2022). Green roof substrates – A literature review. *Frontiers in Built Environment*, 8. DOI:10.3389/fbuil.2022.1019362.
- Katsoulas, N., Savvas, D., Kitta, E., Bartzanas, T., and Kittas, C. (2015). Extension and evaluation of a model for automatic drainage solution management in tomato crops grown in semi-closed hydroponic systems. *Computers and Elec-*

- tronics in Agriculture*, 113, 61–71. DOI:10.1016/j.compag.2015.01.014.
- Khan, S., Irshad, S., Mehmood, K., Hasnain, Z., Nawaz, M., Rais, A., Gul, S., Wahid, M.A., Hashem, A., Abd Allah E.F., and Ibrar, D. (2024). Biochar production and characteristics, its impacts on soil health, crop production, and yield enhancement: a review. *Plants*, 13(2). DOI:10.3390/plants13020166.
- Kim, S.-H., Ochar, K., Hwang, A., Lee, Y.-J., and Kang, H.J. (2024). Variability of glucosinolates in pak choy (*Brassica rapa* subsp. *chinensis*) germplasm. *Plants*, 13(1), 9. DOI:10.3390/plants13010009.
- Kormanek, M., Malek, S., Banach, J., and Durlo, G. (2023). Effect of changing substrate density and water application method on substrate physical properties and container-grown seedling growth. *Forests*, 14(7). DOI:10.3390/f14071490.
- Lakhiar, I.A., Yan, H., Zhang, C., Wang, G., He, B., Hao, B., Han, Y., Wang, B., Bao, R., Syed, T.N., Chauhdary, J.N., and Rakibuzzaman, M. (2024). A review of precision irrigation water-saving technology under changing climate for enhancing water use efficiency, crop yield, and environmental footprints. *Agriculture*, 14(7). DOI:10.3390/agriculture14071141.
- Lynch, J.P. (2018). Rightsizing root phenotypes for drought resistance. *Journal of Experimental Botany*, 69(13), 3279–3292. DOI:10.1093/jxb/ery048.
- Martins, T.C., Machado, R.M.A., Alves-Pereira, I., Ferreira, R., and Gruda, N.S. (2023). Coir-based growing media with municipal compost and biochar and their impacts on growth and some quality parameters in lettuce seedlings. *Horticulturae*, 9(1). DOI:10.3390/horticulturae9010105.
- Méndez-Cifuentes, A., Valdez-Aguilar, L.A., Cadena-Zapata, M., Alvarado-Camarillo, D., and González-Fuentes, J.A. (2023). Nutrient solution electrical conductivity affects yield and growth of sub-irrigated tomatoes. *Horticulturae*, 9(7). DOI:10.3390/horticulturae9070826.
- Müllers, Y., Postma, J.A., Poorter, H., Kochs J., Pflugfelder D., Schurr, U., van Dusschoten, D. (2022). Shallow roots of different crops have greater water uptake rates per unit length than deep roots in well-watered soil. *Plant and Soil*, 481(1–2), 475–493. DOI:10.1007/s11104-022-05650-8.
- Nair, C.S., Alsudain, M.B.H., Manoharan, R., Nishanth, D., Subramanian, R., Manga, A., and Jaleel, A. (2024). Sandponics: a sustainable agriculture solution for food security and resource efficiency in arid regions. *Journal of Sustainable Agriculture and Environment*, 3(4). DOI:10.1002/sae2.70033.
- Nikolaou, G., Neocleous, D., Christou, A., Polycarpou, P., Kitta, E., and Katsoulas, N. (2021). Energy and water related parameters in tomato and cucumber greenhouse crops in semi-arid Mediterranean regions. A Review, Part II: Irrigation and Fertigation. *Horticulturae*, 7(12), 548. DOI:10.3390/horticulturae7120548.
- Pérez-Cabrera, C.A., Juárez-López, P., Anzaldo-Hernández, J., Alia-Tejacal, I., Gayosso-Rodríguez, S., Salcedo-Pérez, E., Guillén-Sánchez, D., Balois-Morales, R., and Cabrera-Chavarría, L.G. (2021). Biocarbón de cascarilla de arroz como sustrato en el crecimiento de plántulas de pepino. *Revista Chapingo, Horticultura*, 27(3). DOI:10.5154/R.RCHSH.2021.01.002.
- Sim, J.-E., Zebro, M., Ahn, J.-Y., Kim, J.-K., Park, H.-K., Shin, A.-Y., Kang, Y.-J., Choi, K.-Y., Kim, S.-H., and Kang, H.-M. (2025). Morphological and Physiological Responses of pak choy (*Brassica rapa* subsp. *chinensis*) Genotypes Under Controlled Drought Stress. *Horticulturae*, 11(12), 1477. DOI:10.3390/horticulturae11121477.
- Steduto, P., Hsiao, T.C., Fereres, E., and Raes, D. (2012). *Crop yield response to water*. Rome: Food and Agriculture Organization of the United Nations, 505p. Available at: <https://openknowledge.fao.org/server/api/core/bitstreams/fb1683eb-df22-438f-b997-a34d44b86ba7/content>
- Verasoundarapandian, G., Zakaria, N.N., Shaharuddin, N.A., Khalil, K.A., Puasa, N.A., Azmi, A.A., Gomez-Fuentes C., Zulkarnain, A., Wong, C.Y., Rahman, M.F., and Ahmad, S.A. (2021). Coco peat as agricultural waste sorbent for sustainable diesel-filter system. *Plants*, 10(11). DOI:10.3390/plants10112468.
- Wang, J., Hu, T., Wang, Y., Wang, W., Hu, H., Wei, Q., Yan, Y., and Bao, C. (2023). Metabolic and transcriptomic analyses reveal different metabolite biosynthesis profiles between purple and green pak choy. *International Journal of Molecular Sciences*, 24(18), 13781. DOI:10.3390/ijms241813781.
- Yang, L., Liu, H., Tang, X., and Li, L. (2022). Tomato evapotranspiration, crop coefficient and irrigation water use efficiency in the winter period in a sunken Chinese solar greenhouse. *Water*, 14(15). DOI:10.3390/w14152410.

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