

Morphophysiological Responses of Pakchoi in Variations of Watering and Growing Media in Vertical Fertigation System

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Abstract. Pakchoi productivity in dryland areas is often constrained by water availability and suboptimal nutrient management strategies. However, the combined role of organic growing media, boron supply, and controlled irrigation in a vertical-wick fertigation system under dryland conditions remains underexplored. This study aimed to assess the presence of boron in compost- and biochar-modified growing media under water stress, which affects the morphophysiology of pakchoi in dryland conditions, using a vertical system with wick fertigation. The study was arranged in a split-plot design with two watering frequencies and a growing media formulation based on soil, compost, and biochar, with added boron. The results showed that watering frequency and boron-based growing media significantly affected leaf number, shoot and root biomass, root characteristics, and chlorophyll content. Consistent daily watering resulted in better growth and yield compared to watering every other day. Optimized combinations of regular irrigations and appropriate boron application enhanced biomass accumulation and chlorophyll content, indicating improved plant performance. These findings indicate that regular water management through a wick fertigation system, combined with organic growing media formulation and appropriate boron dosage, can significantly enhance pakchoi growth and productivity in dryland conditions. Importantly, this study provides a practical and scalable strategy for improving vegetable production under water-limited conditions.

Keywords: biochar; boron; compost; dry land; water

1. Introduction

The agroecosystem on Timor Island, East Nusa Tenggara has low soil quality as a growing medium for plants, shallow solum, lots of rocks, low rainfall (<2,000 mm year⁻¹) and a dry season of 7-8 months ([Matheus et al., 2017](#)). Management must be oriented toward adopting production technologies, improving soil quality and productivity, and providing appropriate nutrients. Vertical farming techniques using fertigation are one such production technology that aims to increase crop yields. This system utilizes vegetable crops such as pakchoi as its target. Pakchoi plants have shallow root systems, making them sensitive to fluctuations in water availability. The fertigation system distributes water and nutrients directly to plant roots along the vertical culture pipe. The fertigation system provides nutrients and their uptake by the roots ([Lestari et al., 2020](#); [Lukmanul, 2021](#)). This technology has shown significant growth and uptake increases in the growth of vertically cultivated pakchoi

([Neonbeni et al., 2022](#); [Tobing et al., 2022](#)). Using this technology, growing media can be modified using compost and biochar. Using both together is more effective than applying them separately ([Kammann et al., 2016](#); [Schmidt et al., 2015](#)). Both applications are able to improve the chemical and microbiological quality of the soil ([Trupiano et al., 2017](#)). The use of both is also able to improve the quality of the growing media and the morphophysiology and yield of pakchoi cultivated vertically with wick fertigation ([Tobing et al., 2024a, 2024b](#)). However, a study of the exact composition percentage of compost and biochar needs to be carried out.

The use of fertigation in vertical culture requires consideration of proper plant nutrition. Nutrient requirements and their provision are crucial because they can impact plant life, particularly roots, which play a crucial role in absorbing nutrients and water from the soil, which are used in plant metabolism. Providing one nutrient through fertilization requires consideration of the



growing medium's conditions, as the nutrient provided will influence the availability of other nutrients in the plant. Boron (B) is an essential micronutrient for plants. B plays a role in plant metabolism, including cell wall and plasma membrane synthesis, phosphorus, phenol, and nitrogen compound metabolism, protein and sugar synthesis, hormonal regulation, and ribonucleic acid (RNA) formation ([García-Sánchez et al., 2020](#); [Vera-Maldonado et al., 2024](#)). B deficiency shows changes in root morphology resulting in an increase in the shoot/root ratio, thickening of the root cell wall mass which inhibits total nutrient absorption and transport ([García-Sánchez et al., 2020](#)). In addition, a decrease in antioxidant enzyme levels, ROS accumulation, photosynthesis rate values, negative effects on photosystem II efficiency, transpiration rate, stomatal conductance, leaf gas exchange, and intercellular CO₂ were found ([García-Sánchez et al., 2020](#); [Wimmer & Eichert, 2013](#)). Toxicity B in plants is the presence of burns, the appearance of chlorotic and necrotic spots on the edges and tips of leaves, reduced proton extrusion in the roots, deposition of suberin and lignin, and nutritional imbalance ([García-Sánchez et al., 2020](#); [Simón-Grao et al., 2018](#)).

The availability of B to plants is closely related to soil water status and its effects on plants. Water scarcity in drylands is often a problem for agriculture. The use of organic materials, such as compost and biochar, can be an alternative for increasing water availability in growing media using soil from drylands. The use of both can increase soil water content, total soil organic carbon, nutrients, and plant growth ([Agegnehu et al., 2016](#)). Regarding differences in growing media, soil compositions amended with compost and biochar significantly increased the fruit weight of cayenne pepper ([Azzahra et al., 2023](#)). Application of compost and biochar can also increase water retention and water use efficiency in sandy soils ([Al-Omran et al., 2021](#)). However, the interaction between B availability and water stress remains insufficiently understood,

particularly in dryland systems. Under water deficit conditions, reduced microbial activity and mineral solubilization may limit B availability to plants. Previous studies reported that combined B deficiency and drought stress significantly reduced biomass and B concentration in rapeseed (*Brassica napus* L) ([Hajibolani & Farhanghi, 2011](#); [Simón et al., 2013](#)). In other findings, B toxicity often occurs in arid and semi-arid areas with groundwater with high B content ([Simón-Grao et al., 2018](#)). Drought can affect the toxicity effects of B when plants are exposed to these stresses simultaneously ([Liu et al., 2018](#)). Plants treated with the highest concentration of B, under water stress, had greater glutathione reductase activity. Inhibition of B and Na⁺ uptake and increased transport of Ca²⁺ and Mg²⁺ from roots to shoots were also found when the two stresses were combined ([García-Sánchez et al., 2020](#)). Other research shows that the inclusion of B can increase plant adaptation to drought by stimulating early stress responses ([Aydin et al., 2019](#)). Although previous studies have explored boron nutrition and drought stress separately, limited research has evaluated their combined effects within modified growing media under a vertical fertigation system in dryland conditions. Therefore, the interaction between boron availability, water stress, and organic amendments in vertically cultivated pakchoi remains insufficiently understood, particularly in dryland regions such as East Nusa Tenggara. This study differs from previous work by investigating how boron supply interacts with modified growing media (compost and biochar) and with watering regimes within a vertical-wick fertigation system. This study aims to evaluate the effects of these interactions on pakchoi's morphophysiological responses under dryland conditions. The findings provide important insights for dryland agriculture, where sustainable nutrient management under limited water availability remains a critical challenge, and where adaptive cultivation strategies are increasingly required to sustain vegetable

production amid intensifying climate variability.

2. Materials and Methods

This research was conducted in an agricultural garden on Jalan Km 07, Sasi Village, Kefamenanu in July-December 2025. Chlorophyll analysis was conducted in the Laboratory of the Faculty of Agriculture, Science, and Health, University of Timor.

The research materials were 4 and 0.5 inch PVC pipes, solder, crowbar, bamboo, 25 L bucket, shovel, soil sieve, analytical balance, spectrophotometer, centrifuge, centrifuge tube, porcelain mortar, jar bottle, measuring cup, cuvette, dropper, oven, stationery, pakchoi vegetable, EM₄, paranet, bran, soil, rice husk, boron fertilizer, molasses, green fodder, flannel cloth, tarpaulin, sacks, used mineral water bottles, analytical balance, oven, aluminum foil, distilled water, and acetone.

This study used an experimental method with a 2-factor Split-Plot Design (SPD). The main plot was the watering variation consisting of: P1 = watering every day and P2 = watering every 2 days. The subplot was boron in the growing media composition consisting of: B1 = 50% soil: compost + 50% biochar with boron 0.5 g.L⁻¹; B2 = 50% soil: compost + 50% biochar with boron 1 g.L⁻¹; B3 = 25% soil: compost + 75% biochar with boron 0.5 g.L⁻¹; B4 = 50% soil: compost + 50% biochar with boron 1 g.L⁻¹; B5 = 75% soil: compost + 25% biochar with boron 0.5 g.L⁻¹; and B6 = 25%: compost + 75% biochar with boron 1 g.L⁻¹. Based on these two factors, 12 experimental combinations were obtained, which were repeated 3 (three) times, resulting in a total of 36 experimental treatments.

The research began with land preparation, the design of vertical pipes for a fertigation system, and the production of biochar and compost. Vertical pipes were made from 4 inch PVC pipes with a height of 1.33 m. Each pipe had 3 planting holes, with 5 planting holes per row spaced 15 cm apart.

The planting holes were formed using a grinder and a heat gun. A wick fertigation system was made from 0.5-inch PVC pipes, 1.5 m high, with holes drilled along the sides of the pipes using a soldering iron. Then, a flannel cloth was inserted as a wick and a plastic bottle was installed at the bottom of the pipe. The biochar was made from rice husks burned with minimal oxygen. The combustion used zinc that had been perforated and rolled. A fire was made inside the zinc roll while standing. The rice husks were placed on the outside of the zinc, following the roll, until they turned black for 3-4 hours. Water was sprinkled if the rice husks had turned black evenly into charcoal, and the fire was extinguished. The compost was made from green fodder. Chop 10 kg of green fodder, mix with 2 kg of bran and 2 kg of molasses, then sprinkle evenly with 15 mL of EM₄ solution diluted with water. Turn the compost twice a week until harvest, 3-4 weeks after composting.

The research began with the cultivation of pakchoi seedlings for 2 weeks. Wick fertigation was performed by inserting the seedlings into vertical culture pipes, with a plastic bottle placed on top of each pipe. The growing media was prepared using ameliorants according to the treatment formulation with a total content of 15 kg per pipe, which was then compacted. The seedlings were transferred to each planting hole in the vertical culture pipe. Each pipe contained 15 plants. The transplanted seedlings had 2-3 leaves and were in healthy condition, free from disease or pest attacks. Plant care was carried out, including watering, fertilization, and pest and disease control if any attacks occurred. Watering was adjusted according to the watering treatment. Fertilization was carried out at the specified treatment concentration. The boron source was a borate fertilizer containing approximately 20% water-soluble boron, applied twice in the vertical-wick fertigation system at 20 and 26 days after transplanting (DAT). The solution was distributed to 15 plants through irrigation channels in each

vertical pipe. Harvesting was carried out 35 days after transplanting (DAT), and observations were made in accordance with the research parameters.

The parameters observed in this study were plant height and number of leaves at 21 and 35 DAT; root length, root volume, fresh weight of the shoot and root, and dry weight of the shoot and root were measured at the end of the study. Root length was measured at the end of the study by measuring from the base to the lowest root. Root volume was calculated at the end of the study by placing it in a 10 mL measuring cup using the formula: $\text{Volume}_2 \text{ (mL)} - \text{Volume}_1 \text{ (mL)}$. Fresh weight was measured at the end of the study by separating the shoot and root and then weighing them with an analytical balance. Dry weight was measured at the end of the study by drying the shoot and root in an oven at 60°C for ±48 hours, then weighing them on an analytical balance. Chlorophyll content was measured every week using a spectrophotometer. Method: Weigh 0.1 g of fresh leaves. Store using aluminum foil. The leaves were then chopped into small pieces and extracted with 10 mL of 80% acetone by grinding them in a mortar. The grinding was carried out until all the chlorophyll dissolved in 80% acetone, characterized by the pulp turning white. The extract was placed in a centrifuge tube for 15 minutes at 3,500 rpm. Using a cuvette, the optical density (OD) of the extract was measured using a spectrophotometer at wavelengths of 645 and 663 nm. The content was calculated by

comparing the OD at wavelengths of 645 and 663 nm according to the equation:

$$\begin{aligned} \text{Total chlorophyll} &= [20.2 \text{ (D645)} \\ &\quad + 8.02 \text{ (D663)}] \times \frac{V}{1000 \times W} \\ \text{Chlorophyll a} &= [12.7 \text{ (D663)} \\ &\quad - 2.69 \text{ (D645)}] \times \frac{V}{1000 \times W} \\ \text{Chlorophyll b} &= [22.9 \text{ (D645)} \\ &\quad - 4.68 \text{ (D663)}] \times \frac{V}{1000 \times W} \end{aligned}$$

The research data were analyzed using analysis of variance. To determine differences in responses between treatments, a mean comparison test using the Duncan Multiple Range Test (DMRT) method at a 5% level was used using SAS software.

3. Results and Discussion

The results of the analysis of variance for the effects of variations in watering and growing media on pakchoi plant height and number of leaves are presented in [Table 1](#). The interaction of watering (P) and boron in the growing media (B) did not significantly affect the height of pakchoi plants ($P > 0.05$). Still, it significantly affected the observation of the number of leaves ($P < 0.05$). Watering variations significantly affected plant height at 21 DAT and the number of leaves at 21 and 35 DAT ($P < 0.05$) but did not significantly affect plant height at 35 DAT. Growing media containing boron significantly affected the number of leaves at 21 DAT ($P < 0.05$) but did not significantly affect plant height or the number of leaves at 35 DAT ($P > 0.05$).

Table 1. Variance analysis data of pakchoi growth observations

Parameters	Interaction between watering variations and growing media (Px B)	Watering (P)	Growing media (B)
Plant Height 21 DAT	0.4988 ^{ns}	0.0113*	0.1223 ^{NS}
Plant Height 35 DAT	0.4988 ^{ns}	0.1237 ^{NS}	0.1858 ^{NS}
Number of Leaves 21 DAT	0.0218*	<.0001*	0.0351*
Number of Leaves 35 DAT	0.0015*	<.0001*	0.1332 ^{NS}

Remarks: ns= Not Significant; *=significant at the 0.05 level

The significant differences in the influence of each treatment, both interactions and single effects on pakchoi growth, can be seen in Table 2. Based on observations of the number of leaves at 21 DAT, the interaction of P1B5 was not significantly different from P2B5, P1B2, and P2B2, while at 35 DAT, P1B5 was not

significantly different from P1B2 (Table 2). Observations of plant height at 21 DAT and the number of leaves at 21-35 DAT showed that treatment P1 was significantly different from P2. In the growing media, observations of the number of leaves at 21 DAT, B1 was not significantly different from all treatments except B4.

Table 2. Effect of watering and growing media on pakchoi growth

Treatments Interaction of Px B	Plant height (cm)		Number of leaves (leaves)	
	21 DAT	35 DAT	21 DAT	35 DAT
P1B1	18.75±0.10	21.70±0.63	8.67±0.16 ^{bcd}	13.17±0.12 ^c
P1B2	18.58±0.05	23.65±0.06	9.67±0.13 ^{ab}	14.50±0.26 ^{ab}
P1B3	16.65±0.50	23.03±0.24	9.00±0.06 ^{bc}	12.67±0.26 ^{cd}
P1B4	17.62±0.23	24.62±0.22	8.67±0.16 ^{bcd}	12.83±0.22 ^{cd}
P1B5	19.47±0.31	24.88±0.29	10.33±0.32 ^a	15.00±0.41 ^a
P1B6	19.32±0.27	25.33±0.42	9.00±0.06 ^{bc}	13.33±0.07 ^{bc}
P2B1	17.73±0.16	22.35±0.02	8.67±0.32 ^{bcd}	12.67±0.20 ^{cd}
P2B2	15.92±0.36	22.88±0.00	9.67±0.08 ^{ab}	11.67±0.09 ^d
P2B3	17.25±0.02	22.20±0.04	9.00±0.11 ^{bc}	12.33±0.10 ^{cd}
P2B4	16.58±0.17	24.85±0.57	8.67±0.30 ^{bcd}	11.50±0.14 ^d
P2B5	17.73±0.16	23.02±0.04	10.33±0.06 ^a	11.50±0.14 ^d
P2B6	17.85±0.19	22.00±0.25	9.00±0.08 ^{bc}	12.17±0.06 ^{cd}
Watering				
P1	18.40±0.17 ^a	23.87±0.14	9.22±0.19 ^a	13.58±0.23 ^a
P2	17.18±0.17 ^b	22.88±0.14	7.89±0.19 ^b	11.97±0.23 ^b
Growing media				
B1	18.24±0.13	22.03±0.39	8.83±0.08 ^a	12.92±0.04
B2	17.25±0.15	23.27±0.03	8.92±0.10 ^a	13.08±0.09
B3	16.95±0.24	22.62±0.22	8.25±0.09 ^{ab}	12.50±0.08
B4	17.10±0.20	24.73±0.39	7.75±0.23 ^b	12.17±0.18
B5	18.60±0.23	23.95±0.17	9.00±0.13 ^a	13.25±0.14
B6	18.58±0.23	23.67±0.08	8.58±0.01 ^{ab}	12.75±0.01

Remarks : Numbers followed by the same letter indicate no significant difference at the 5% α level according to the DMRT test.

Watering and boron in the growing media have been shown to significantly influence pakchoi of leaf number compared to plant height. This phenomenon is due to the physiological nature of leaf cell initiation and division in the apical meristem, which is highly sensitive to turgor pressure and the availability of essential microelements such as boron. Stable humidity during the daily watering treatment (P1) increases tissue water potential and facilitates mass flow, thereby increasing boron absorption efficiency (Alonso-Serra et al., 2024). Boron

has an important role in the formation of the borate–rhamnogalacturonan II (RG-II) complex, which strengthens the primary cell wall and supports cell division and differentiation in young tissues (Funakawa & Miwa, 2015; Vera-Maldonado et al., 2024). The combination of optimal water availability and sufficient boron will accelerate leaf meristem activity and increase the initiation of new leaves. Conversely, under conditions of watering every two days (P2), fluctuations in media humidity reduce cell turgor and inhibit boron transport to

meristematic tissue, thereby causing the rate of new leaf formation to decrease faster than the rate of stem elongation (Rékási et al., 2021). The process of plant height increase is more dependent on cell expansion regulated by growth hormones such as auxin and gibberellin, which require accumulative time to show a real response to variations in water and micro elements (Varner et al., 2024). In addition, studies show that boron plays a role not only in cell division but also in regulating the transport of photosynthates to young organs, which directly contributes to the formation of new leaves. (Shireen et al., 2018). Thus, the synergistic effect between stable media moisture and boron availability is more quickly reflected in increased leaf number than in plant height growth. These results are consistent with recent reports on the relationship between soil water status, boron uptake efficiency, and shoot morphogenesis activity in plants (Huntenburg et al., 2025).

The interaction between watering and growing media + boron ($P \times B$) at the age of 21 and 35 DAT, the roots have matured more, and the media has begun to reach hydraulic equilibrium, indicating that daily watering (P1) allows for continuous water mass flow and more efficient boron absorption (Vera-Maldonado et al., 2024; Chu et al., 2025). Boron plays an important role in the regulation of shoot meristems and cell division (structural function of the walls and regulation of leaf development) (Chu et al., 2025; Pereira et al., 2021). The combination of stable humidity and optimal boron dosage increases leaf initiation activity. This causes the P1B5 to consistently produce the highest number of leaves at both observation times. This suggests that daily watering combined with a growing medium containing 75% soil: compost + 25% biochar with boron 0.5 g.L^{-1} provided more favorable conditions for leaf initiation and expansion. Conditions that increase moisture retention and stability and improve root conditions, can improve root access to B and strengthen leaf formation (Premalatha et al., 2023). However, compost

and biochar can also retain or adsorb B so that the effect depends on the interaction between watering and the media modification given boron.

The significant effect of watering at 21 days after planting indicates that the active vegetative growth phase of pakchoi is highly responsive to soil water status. At this stage, plants undergo intensive cell division and expansion, particularly in young leaf and stem tissues. Adequate water availability (P1) maintains cell turgor, thus supporting new tissue division and differentiation, resulting in a significant increase in height and leaf number (Gong et al., 2020; Taiz et al., 2023). However, at 35 days after planting, plant height growth begins to slow as it enters the final vegetative maturation phase. Growth is more focused on leaf expansion and thickening than stem elongation. This results in the effect of watering on plant height being less significant, while leaf number remains affected because new leaf formation is still occurring and dependent on water supply and photosynthetic activity (Li et al., 2023). In addition, more frequent watering increases the efficiency of micronutrient absorption, including boron, which plays an important role in the formation of leaf meristematic tissue (Patel et al., 2023). In contrast, height growth is more dependent on hormonal regulation such as auxin and gibberellin, which tend to stabilize after the initial growth phase (Taiz et al., 2023). Therefore, at later ages, the effect of watering appears to be stronger on morphogenetic aspects (number of leaves) than on morphometric aspects (plant height).

The compost + biochar with boron growing media did not significantly affect pakchoi height, but did affect leaf number, particularly at 21 days after planting. Plant height (elongation) was insensitive to variations in B availability or changes in the growing medium properties. Leaf number (meristem initiation/division) was more sensitive to micro-rhizosphere conditions (local humidity, availability of absorbable B), so the effect of B on leaf number emerged at

21 days after planting, when the roots/medium were more stable. Stem elongation is influenced by hormone-mediated cell expansion (auxin, gibberellin) and the general availability of metabolic resources; small changes in micro-availability ($0.5 - 1 \text{ g.L}^{-1}$) or in the physical properties of the medium (variation in biochar 25–75%) may not be sufficient to alter hormonal/cell expansion pathways and thus produce significant differences in height. Elongation is often more resistant to micro-nutrient fluctuations than are new organ formation parameters in horticultural crops (Yang et al., 2024). Leaf initiation in the meristem is highly dependent on cell turgor and the supply of assimilates and microelements necessary for cell division. Boron plays a role in cell wall integrity (cross-linking RG-II pectin) and carbohydrate transfer, a direct function that rapidly influences the formation of young leaves (Chu et al., 2025). Once the roots are more established (21 DAT), mass flow becomes more consistent, increasing B uptake and its effects on leaf division/initiation become apparent (Lou et al., 2001). Compost and biochar in the growing medium play a role in increasing water retention and modifying the adsorption and desorption properties of micronutrients, including boron. The biochar-compost combination significantly improves water retention capacity and soil fertility and enhances micronutrient uptake (Manirakiza & Şeker, 2020). With more frequent watering to maintain stable media moisture, boron uptake becomes more efficient, and its effects on young leaf formation are clearly visible. This indicates that the interaction between watering and boron in the growing medium is more significant than the effect of boron in the growing medium alone.

The significant differences in the effects of each treatment, both interactions and main effects, on pakchoi yield are shown in Table 3. Overall, pakchoi yields were influenced by the interaction between watering variation and boron in the growing media composition

treatments. Daily watering generally resulted in higher shoot biomass and improved root development compared to watering every two days, indicating that stable moisture conditions supported better plant growth under the vertical cultivation system. The interaction effects revealed that certain combinations under daily watering enhanced yield components more consistently than others. Observations of the fresh weight of the shoots showed that the P1B2 interaction was not significantly different from those of P1B5 and P1B6. This also occurred for root length. However, observations of shoot dry weight showed that P1B5 differed significantly from the other interactions. In terms of fresh root weight, P1B2 was not significantly different from P1B5, P1B6, P2B3, and P2B1. Observations of shoot dry weight showed that P2B1 differed significantly from the other interactions. In terms of root volume, P1B5 was not significantly different from P2B2.

Watering treatment, as observed in fresh and dry shoot weight and fresh root weight, showed that P1 differed significantly from P2. The growing media treatment in each observation showed different significant results. In the fresh weight of the shoot, B2 differed significantly from B5 and B6. However, in the shoot dry weight, B2 and B5 showed the same significant performance as the other growing media treatments. In the observation of root weight, B2 was not significantly different from other growing media treatments except B4, but in the root dry weight, B1 was not significantly different from B2 and B3. Observations of root length showed that B5 was not significantly different from B5, but in root volume, B5 was not significantly different from B4.

Treatments P1B6, P1B2, and P1B5 showed optimal shoot and root biomass accumulation. This pattern suggests that daily watering (P1) increases leaf biomass accumulation because a stable water supply maintains turgor and photosynthetic activity, while watering every other day (P2) causes mild water stress that suppresses cell

expansion and photosynthetic product translocation (Hussain et al., 2019). Stable water availability supports the process of photosynthesis, cell turgor, and assimilate transport to the canopy organs, which are essential for overall plant growth and development (Xiong & Nadal, 2020). Maintaining soil moisture through regular watering also increases the efficiency of absorption of microelements, including boron, which plays an important role in cell division and the formation of young tissue (Wimmer & Eichert, 2013). Meanwhile, in

terms of root fresh weight, the combination of P1B2 and P1B5 showed high values but was not significantly different from P2B1 and P2B3, indicating that less frequent watering (P2) can trigger an adaptive response characterized by increased root biomass. This condition is a physiological adaptation mechanism to expand water exploration under conditions of humidity fluctuations (Yang et al., 2021; Kou et al., 2022). Thus, more frequent water treatments focused on shoot formation, while mild water stress in P2 shifted biomass allocation to the root system.

Table 3. Effect of watering and growing media on pakchoi yield

Treatments Interaction of PxB	Shoot		Root			
	Fresh weight (g)	Dry weight (g)	Fresh weight (g)	Dry weight (g)	Length (cm)	Volume (mL)
P1B1	57.90±7.31 ^d	3.16±0.32 ^e	2.25±0.20 ^{cd}	0.34±0.03 ^{ef}	9.62±0.52 ^f	2.33±0.00 ^{cd}
P1B2	95.02±3.40 ^a	4.98±0.20 ^b	3.52±0.16 ^a	0.57±0.04 ^{ab}	12.40±0.29 ^{ab}	1.63±0.20 ^e
P1B3	69.77±3.89 ^{bc}	3.28±0.29 ^e	2.40±0.16 ^{cd}	0.37±0.02 ^{de}	11.18±0.06 ^{cd}	1.60±0.21 ^e
P1B4	77.58±1.63 ^b	4.14±0.04 ^c	2.78±0.05 ^{bc}	0.41±0.01 ^d	9.90±0.44 ^{ef}	2.73±0.12 ^{bc}
P1B5	97.70±4.18 ^a	5.37±0.31 ^a	3.43±0.14 ^a	0.50±0.02 ^c	12.97±0.45 ^a	3.58±0.36 ^a
P1B6	101.43±5.25 ^a	4.76±0.14 ^b	3.35±0.11 ^a	0.41±0.01 ^d	12.38±0.28 ^{ab}	2.09±0.07 ^d
P2B1	62.35±0.15 ^{cd}	3.47±0.02 ^{de}	3.12±0.12 ^{ab}	0.61±0.06 ^a	10.90±0.11 ^{cd}	1.54±0.27 ^e
P2B2	69.72±1.98 ^{bc}	3.77±0.06 ^d	2.40±0.08 ^{cd}	0.38±0.01 ^{de}	10.85±0.13 ^{cd}	3.33±0.25 ^a
P2B3	65.18±0.67 ^{cd}	3.75±0.06 ^d	3.48±0.23 ^a	0.55±0.04 ^b	11.70±0.12 ^{bc}	2.48±0.00 ^{bcd}
P2B4	62.97±0.03 ^{cd}	3.51±0.01 ^{de}	2.27±0.12 ^{cd}	0.31±0.03 ^{fg}	10.58±0.20 ^{de}	2.85±0.11 ^b
P2B5	59.75±0.90 ^d	3.36±0.06 ^e	2.17±0.15 ^d	0.28±0.04 ^g	11.60±0.09 ^{bc}	2.27±0.06 ^d
P2B6	57.22±1.63 ^d	3.45±0.03 ^{de}	2.73±0.01 ^{bc}	0.38±0.01 ^{de}	12.08±0.23 ^b	2.33±0.04 ^{cd}
Watering						
P1	83.23±2.94 ^a	4.28±0.11 ^a	2.96±0.04 ^a	0.43±0.00	11.41±0.02	2.33±0.02
P2	62.86±2.94 ^b	3.55±0.11 ^b	2.69±0.04 ^b	0.42±0.00	11.29±0.02	2.47±0.02
Growing media						
B1	60.13±3.73 ^c	3.32±0.17 ^d	2.68±0.04 ^{ab}	0.47±0.01 ^a	10.26±0.31 ^c	1.94±0.13 ^c
B2	82.37±2.69 ^a	4.38±0.13 ^a	2.96±0.04 ^a	0.48±0.01 ^a	11.63±0.08 ^b	2.48±0.02 ^b
B3	67.48±1.61 ^b	3.52±0.12 ^d	2.94±0.03 ^a	0.46±0.01 ^a	11.44±0.03 ^b	2.04±0.10 ^c
B4	70.28±0.80 ^b	3.83±0.03 ^c	2.53±0.09 ^b	0.36±0.02 ^b	10.24±0.32 ^c	2.79±0.11 ^a
B5	78.73±1.64 ^a	4.36±0.13 ^a	2.80±0.01 ^{ab}	0.39±0.01 ^b	12.28±0.27 ^a	2.93±0.15 ^a
B6	79.33±1.81 ^a	4.11±0.05 ^b	3.04±0.06 ^a	0.39±0.01 ^b	12.23±0.26 ^a	2.21±0.05 ^c

Remarks : Numbers followed by the same letter indicate no significant difference at the 5% α level according to the DMRT test.

In addition to boron content, the percentage of organic media influenced the distribution of plant biomass. For example, P1B5 and P1B6 with high organic content increased shoot weight because the media was able to retain water and support optimal photosynthesis, while P1B2, with a more balanced media composition (50% soil: 50% compost + biochar), showed a balance between shoot and root growth. This suggests that high percentages of compost and biochar

(B5 and B6) exhibited better water retention capacity, increased micro-humidity stability around the roots, and improved aeration and cation exchange capacity (Safitri et al., 2018). This allows the roots to utilize nutrients more efficiently, increasing root and shoot weight (Wang et al., 2023). The combination of biochar and compost also modifies boron adsorption, allowing for more controlled release of micronutrients and their availability to plants when needed. Overall,

the interaction between watering frequency (P), boron, and growing media composition (soil, compost, biochar) results in a complex yet coordinated growth pattern: regular watering supports canopy formation, optimal boron content promotes cell division, and a medium-high compost and biochar content stabilizes moisture and nutrient availability. This pattern is consistent with previous research emphasizing the importance of a combination of abiotic factors and growing medium in enhancing vegetable plant biomass accumulation (Vera et al., 2023).

A similar pattern was also observed in shoot and root dry weights (Table 3). Treatments P1B2, P1B5, and P1B6 produced the highest shoot dry weights, indicating that boron plays an active role in strengthening cell walls and in the formation of new photosynthetic tissue. Boron facilitates the formation of borate complexes with rhamnogalacturonan-II (RG-II) in the cell wall, increasing tissue stiffness and photosynthetic efficiency (Begum & Fry, 2023). Meanwhile, watering every two days (P2) significantly reduced the dry weight of the shoots, presumably due to decreased turgor and enzymatic activity during carbon transport. Root dry weight showed smaller variations between treatments, with no significant differences between P1 and P2. These results indicate that the root system exhibits high morphological plasticity in response to variations in water and boron availability, with plants maintaining a balance between root tissue expansion and density to enable efficient water and nutrient uptake (Jia et al., 2022). This confirms that the role of boron in roots is indirect and more limited due to its slow movement in the phloem tissue (Lewis, 2019). Treatments P1B5 and P1B2 produced the highest root lengths, followed by P1B6, indicating that the optimal combination of boron with a media containing high levels of compost and biochar supports root cell proliferation and elongation. Root length increased in media with a high percentage of compost-biochar (B5 = 25% soil : 75% compost + biochar; B6

= 25% soil : 75% compost + biochar) because the medium increased water retention, aeration, and the availability of absorbable boron. Boron supports root cell division and differentiation through the formation of strong cell walls and the regulation of root growth hormones such as auxin (Chen et al., 2023). Daily watering (P1) helps maintain optimal humidity so that root elongation can occur without being hampered by cell turgor fluctuations. In contrast, in P2 watering, despite less frequent watering, roots show adaptation by maintaining their length at certain boron doses (B2, B5), which indicates a compensatory mechanism to increase water exploration in deeper layers of the medium (Riaz et al., 2018). This pattern confirms that high-organic media (compost + biochar) work synergistically with boron to maximize root growth.

Root volume observations followed a similar pattern to root length (Table 3). The interaction between $P \times B$ and boron dose was significant, while single irrigation was not. Treatments P1B5 and P1B2 produced the highest root volume. This is due to the high compost-biochar medium, which increases porosity and water retention capacity, allowing roots to optimally absorb water and boron for proliferation and lateral tissue development. Higher root volume supports water and nutrient absorption, thereby further enhancing shoot growth. Boron increases root meristem cell division and cell wall integrity, resulting in thicker and more branched roots (Mei et al., 2016; Riaz et al., 2018). Regular watering (P1) stabilized turgor and supported boron and assimilate transport to the roots, enhancing the effect of the compost-biochar-rich growing medium. Data on root length and root volume showed no significant differences between waterings (P1 and P2), although the combination of treatments with moderate boron (B5 and B6) produced the highest values. These results demonstrate that the pakchoi root system is capable of maintaining growth under moderate water fluctuations, utilizing boron's role in stabilizing the plasma membrane and

regulating root cell elongation (Riaz et al., 2018; Shireen et al., 2018). The combination of compost and biochar in the growing media is also thought to play an important role in maintaining moisture and increasing boron retention and the availability of micronutrients in a sustainable manner (Elkhlifi et al., 2023; Mikajlo et al., 2024).

The significant differences in the influence of each treatment, both interactions and single effects on the chlorophyll content of pakchoi are shown in Table 4. Observations on chlorophyll a, the interaction of P1B1 was not significantly different from P1B2 and P1B6. However, in chlorophyll b,

P1B1 differed significantly from the other interactions. The interaction of P1B1 was significantly different from P1B2, P1B6, P2B5, and P2B6 in total chlorophyll observations. Observations of all chlorophyll levels, the watering treatment P1 was significantly different from P2. For the effect of the growing media on chlorophyll, an observation was made that B6 was significantly different from other interactions. In chlorophyll b levels, B6 was not significantly different from B1, B2, and B5. Meanwhile, in total chlorophyll, B6 was significantly different from B1 and B5.

Table 4. Effect of watering and growing media on chlorophyll levels in pakchoi

Interaction of PxB	Chlorophyll a	Chlorophyll b	Total chlorophyll
P1B1	1.42±0.08 ^a	0.48±0.04 ^a	1.89±0.12 ^a
P1B2	1.28±0.04 ^{ab}	0.38±0.01 ^b	1.65±0.06 ^{abc}
P1B3	1.01±0.04 ^{de}	0.27±0.02 ^{cd}	1.28±0.05 ^{cde}
P1B4	0.67±0.13 ^f	0.17±0.04 ^e	0.84±0.18 ^{fg}
P1B5	1.07±0.02 ^{cd}	0.32±0.00 ^{bc}	1.39±0.02 ^{bcd}
P1B6	1.35±0.06 ^{ab}	0.36±0.01 ^b	1.71±0.07 ^{ab}
P2B1	0.85±0.01 ^{ef}	0.24±0.00 ^{cde}	1.09±0.01 ^{def}
P2B2	0.81±0.02 ^f	0.22±0.01 ^{de}	1.03±0.03 ^{defg}
P2B3	0.74±0.04 ^f	0.18±0.02 ^{de}	0.92±0.06 ^{efg}
P2B4	0.48±0.12 ^g	0.19±0.02 ^{de}	0.67±0.13 ^g
P2B5	1.21±0.10 ^{cd}	0.31±0.02 ^{bc}	1.52±0.11 ^{abc}
P2B6	1.18±0.09 ^{bcd}	0.35±0.03 ^b	1.54±0.12 ^{abc}
Watering			
P1	1.13±0.04 ^a	0.33±0.01 ^a	1.46±0.05 ^a
P2	0.88±0.04 ^b	0.25±0.01 ^b	1.13±0.05 ^b
Growing media			
B1	1.13±0.04 ^b	0.36±0.02 ^a	1.49±0.06 ^{ab}
B2	1.04±0.01 ^b	0.30±0.00 ^a	1.34±0.01 ^{bc}
B3	0.88±0.04 ^c	0.22±0.02 ^b	1.10±0.06 ^c
B4	0.57±0.12 ^d	0.18±0.03 ^b	0.76±0.15 ^d
B5	1.14±0.04 ^b	0.31±0.01 ^a	1.45±0.05 ^{ab}
B6	1.27±0.08 ^a	0.35±0.02 ^a	1.62±0.09 ^a

Remarks : Numbers followed by the same letter indicate no significant difference at the 5% α level according to the DMRT test.

Chlorophyll A acts as the primary reaction pigment in photosystems II and I, capturing light energy for key photochemical reactions. Data show that the highest chlorophyll A levels are found in the combination of P1B1, P1B2, P1B6, and P2B5. Daily watering (P1) provides stable

humidity for optimal cell turgor, supporting chlorophyll A synthesis and increasing the efficiency of electron transfer in the thylakoid (Dalal, 2021; Rawat et al., 2017). The combination of growing media with optimal boron and a high proportion of compost and biochar (B6) increases water retention, boron

availability, and thylakoid membrane stability, so that chlorophyll A biosynthesis is more efficient and the photosystem is able to function optimally ([Abideen et al., 2024](#); [Bai et al., 2023](#)). Chlorophyll B functions as an antenna pigment, capturing additional light and channeling it to chlorophyll A to increase the light spectrum used in photosynthesis. The highest chlorophyll B levels were observed in P1B1, P1B2, and P2B6. The effect of daily watering (P1) increased water supply and photosynthetic activity, while the medium with a high organic content helped maintain micro-humidity around the roots, supporting boron absorption, which is essential for chlorophyll B stability ([Song et al., 2023](#)). It should be noted that P2B6 showed that high organic media can somewhat compensate for the effects of less frequent watering, as the maintained micro-humidity allows chlorophyll B synthesis to remain optimal ([Nadeem et al., 2017](#)). Total chlorophyll is the accumulation of chlorophyll A and B, reflecting the overall photosynthetic capacity of the leaf. The highest value was observed in P1B1, significantly different from the other treatments. The dominant effect of daily watering indicates that water availability is the primary factor in determining total chlorophyll content. A growing medium rich in compost and biochar supports water retention and boron availability, increasing overall photosynthetic efficiency, expanding the leaf's ability to capture light, and maximizing the rate of carbon assimilation ([Abideen et al., 2024](#)). Thus, the interaction effect of watering and boron in the growing media increases the accumulation of chlorophyll A and B, so that the total chlorophyll content becomes optimal.

4. Limitations and Future Directions

This research has several limitations. It was conducted during a single planting period, so the response was context-specific to the dryland agroecosystem conditions, and plant stress was controlled through irrigation

using a vertical culture system with wick fertigation. Long-term field validation across multiple planting seasons and different dryland environments was also not conducted, limiting the broader generalization of the findings. Future research should assess physiological parameters such as stomatal conductance, photosynthetic rate, and boron uptake dynamics to better understand plant adaptation mechanisms under water-limited conditions. Furthermore, long-term multi-season trials and quality-based yield evaluations are necessary to validate the stability and practical scalability of vertical-wick fertigation systems in real-world dryland vegetable production.

5. Conclusion

This study shows that the frequency of watering and boron application in a growing media modified with compost and biochar play an important role in determining the morphophysiological response of pakchoi in a vertical culture system with wick fertigation. Daily watering with 1 g.L⁻¹ boron in a medium of 50% soil : 50% compost + biochar or the use of 0.5 g.L⁻¹ boron in a medium of 25% soil : 75% compost + biochar produces the same performance in leaf formation, accumulation of shoot and root biomass, root architecture, and leaf chlorophyll content. Watering frequency is the main controlling factor, where consistent daily watering increases leaf growth, yield, and chlorophyll content of pakchoi. These findings support the adoption of vertical-wick fertigation systems with optimized nutrient and water management as a scalable technological approach to improving vegetable productivity and water use in dryland agriculture, thereby contributing to sustainable intensification strategies.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, the author utilized artificial intelligence (AI)

technology to assist with language editing. After using this tool, the author reviewed and edited the entire manuscript as needed and takes full responsibility for the scientific substance, data interpretation, and conclusions presented in this manuscript.

Authorship Contribution Statement

Wilda Lumban Tobing: Conceptualization, Methodology, Investigation, Format Analysis, Data Curation, Writing (Original Draft, Review, and Editing), Visualization, and Conclusion Formulation. Azor Yulianus Tefa: Investigation (Boron Fertilizer Treatments), Methodology, Chlorophyll Measurement, Data Collection, and Writing (Review and Editing). Natalia Desy Djata Ndua: Investigation (Soil Sampling and Growing Media Modification), Methodology, Data Collection, and Writing (Review and Editing).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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