Jurnal Agronomi Indonesia
(Indonesian Journal of Agronomy)

ISSN 2085-2916 | e-ISSN 2337-3652
August 2026, *54*(2), 89-101
DOI: https://dx.doi.org/10.24831/jai.v54i2.72423

Research Article

Growth and yield responses of pak choi to application of water hyacinth-based compost and banana stem PGPR in alluvial soil

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Received:
1 April 2026

Revised:
15 August 2026

Accepted:
15 September 2026

Citation:
Suryani, R., Sutikarini, S., Irianti, A. T. P., Hayat, E. S. (2026). Growth and yield responses of pak choi to application of water hyacinth-based compost and banana stems PGPR in alluvial soil. *Jurnal Agronomi Indoneia (Indonesian Journal of Agronomy), 54*(2), 89-101.https://dx.doi.org/10.24831/jai.v54i2.72423

Abstract

Pak choi (Brassica rapa L.) is a very popular vegetable, but its productivity is still low in West Kalimantan's alluvial soils because of low soil fertility. Plant productivity and soil quality may be improved by adding plant growth-promoting rhizobacteria (PGPR) to water hyacinth-based compost and banana stems. This study aimed to evaluate the application of water hyacinth-based compost and banana-stem-originated PGPR on the growth and yield of pak choi in alluvial soil. The experiment was conducted in Pal IX, Kubu Raya, using a two-factor completely randomized design (CRD) with three replicates. The first factor was compost level (0, 50, and 100 g per polybag), and the second factor was PGPR concentrations (5, 10, and 15 mL L^{-1}). Plant height, leaf number, shoot fresh weight, root fresh weight, chlorophyll content, and root volume were evaluated. Results showed there was an interaction effect of treatments on plant height, while other variables were mainly influenced by compost. Application of water hyacinth-based compost significantly improved plant growth and chlorophyll content, indicating its potential to enhance pak choi performance. On the other hand, PGPR concentrations did not produce significant differences in plant growth and chlorophyll content. Compost application at levels of 50 and 100 g per polybag improved pak choi growth and biomass as compared to the control treatment.

Keywords: leafy vegetables; plant growth; *Pontederia crassipes*; soil fertility; sustainable agriculture

Introduction

Pak choi (*Brassica rapa* L.) is a popular vegetable in Indonesia, including West Kalimantan. This vegetable contains a high vitamin A (approximately 4,468 IU per 100 g, or about 149% of the recommended daily value) and vitamin C (approximately 45 mg per 100 g, or about 75% of the recommended daily value), along with essential minerals such as calcium, potassium, and iron, leading to a continuous increase in demand as awareness of healthy eating grows (BPS, 2023; FAO, 2022).

Annually, West Kalimantan produces 4,036 to 4,277.50 tons of leafy vegetables, including pak choi (BPS, 2025). Pak choi contributes about 70% of annual vegetable production. The production area is mostly on alluvial soil; the alluvial soil covers approximately 2.0 million ha, or about 10.3% of province agriculture land. The alluvial lays along the coastal areas, has high clay content, poor drainage, low organic matter, and tends to be acidic. These conditions limit aeration, root development, and the availability of essential nutrients (Bhattacharyya et al., 2008; Havlin et al., 2014).

Brassica species generally grow optimally at a pH of 5.5–6.5. In West Kalimantan, however, pak choi production fluctuated annually. Based on preliminary evaluation, soil acidity and low organic matter limited the production. According to Havlin et al. (2014), acidic soil reduces phosphorus availability and increases Al toxicity. Alluvial soil can be improved by adding organic matter. It improves soil aggregation, water retention, microbial activity, and nutrient use efficiency (Bhattacharyya et al., 2008).

One potential source of organic matter is water hyacinth (*Pontederia crassipes* Mart. syn *Eichhornia crassipes* (Mart.) Solms) or *eceng gondok* in Indonesian. This plant is known as an aquatic weed with a high growth rate and is widely abundant in many tropical water bodies, often causing serious ecological and water management problems due to its excessive proliferation (Rezania et al., 2016). Its abundant availability and underutilized biomass make water hyacinth a readily accessible and low-cost organic resource for agricultural applications. Water hyacinth biomass contains sufficient nitrogen, phosphorus, and potassium, making it a potential source for compost (Hasono et al., 2026; Rezania et al., 2016).

Furthermore, improvements in soil biological properties through the application of plant growth-promoting rhizobacteria (PGPR) have been widely evaluated. PGPR functions through mechanisms such as nitrogen fixation, phosphate solubilization, production of indole-3-acetic acid (IAA), and control of soil-borne pathogens (Backer et al., 2018; Glick, 2012; Vessey, 2003). The integration of organic fertilizers and PGPRs can enhance nutrient uptake efficiency while improving soil health. The application of PGPR has been reported to influence the growth and yield of pak choi, although plant responses may vary depending on PGPR concentration, growing conditions, and material for production (Probojati et al., 2022; Sari et al., 2022).

The addition of compost and PGPR enhances soil organic matter and microbial activity, which in turn modifies the rhizosphere conditions and promotes greater photosynthetic capacity as well as more efficient nutrient uptake (Antonius et al., 2021; Sari et al., 2022). Application of organic fertilizer derived from banana stems has been reported to enhance the growth and yield of pak choi by improving soil physicochemical properties and stimulating plant physiological processes (Rekanta & Sumiahadi, 2025).

Many studies have examined the effect of water hyacinth-based compost and banana stem-derived PGPR application. However, the combined effect of such treatments on the growth and physiological responses of pak choi in alluvial soil remains limited. This study, therefore, investigated the application of water hyacinth-based compost and banana-stem-derived PGPR on the growth and yield of pak choi in alluvial soil.

Materials and methods

Time and location of the study

This study was carried out in Pal IX, Kubu Raya Regency, West Kalimantan. The experiment was conducted from May to July 2025. The time started from the preparation of water hyacinth-based compost and PGPR until the harvest of pak choi.

Soil was evaluated before the experiment. The evaluation was conducted at the Laboratory of Soil Chemistry and Fertility, Faculty of Agriculture, Universitas Tanjungpura. The soil was strongly acidic, with pH H_2O and pH KCl values of 4.98 and 4.07, respectively. The soil contained 2.08% organic C and 0.26% total N, corresponding to a C/N ratio of approximately 8, while available P (Bray I) was low at 9.23 ppm. Exchangeable cations were dominated by Ca (2.85 cmol(+) kg^{-1}), followed by Mg (0.87 cmol(+) kg^{-1}), Na (0.31 cmol(+) kg^{-1}), and K (0.26 cmol(+) kg^{-1}), with a cation exchange capacity (CEC) of 16.75 cmol(+) kg^{-1} and a base saturation of 25.61%. Exchangeable Al and H were 0.51 and 0.46 cmol(+) kg^{-1}, respectively, consistent with the acidic reaction of the soil. Particle-size analysis indicated a silt loam texture, comprising 0.00% sand, 75.29% silt, and 24.71% clay. Thus, the soil had strong acidity, low organic matter and available P, and low base saturation.

Ready to use of water hyacinth-based compost was analyzed before application. The analysis showed a pH of 7.41, an organic C content of 43.12%, a total N content of 2.55%, and a C/N ratio of 16.91. Extraction with 1:2 HCl showed P, K, Ca, and Mg contents of 2.27%, 2.25%, 0.29%, and 0.57%, respectively. These characteristics confirmed that the compost had reached maturity, with a near-neutral pH and a C/N ratio close to the threshold generally considered suitable for organic amendments, and was therefore appropriate for use in the growing medium.

Experimental design

The experiment was arranged in a completely randomized design (CRD) with a factorial scheme involving two treatment factors. The first factor was the level of water hyacinth-based compost, which comprised three levels: 0, 50, and 100 g per polybag. The second factor was PGPR concentration, consisting of three levels: 5, 10, and 15 mL L^{-1}. From these two factors, 9 treatment combinations were obtained with 3 replicates, resulting in a total of 27 experimental units. Each experimental unit consisted of 3 plants, resulting in a total of 81 plants observed.

All treatments received PGPR at one of the three concentrations (5, 10, or 15 mL L^{-1}). No control treatment of PGPR (0 mL L^{-1}) was included. The reason without control was to compare responses among PGPR concentrations within an integrated compost-PGPR system rather than to test the presence versus absence of PGPR. Consequently, the results and conclusions regarding PGPR in this study are limited to differences among the tested concentrations and do not represent an assessment of the general effectiveness of PGPR application relative to no PGPR application.

The study used Nauli variety pak choi seeds. Pak choi seeds were sown in a seedling medium for 14 days until they had 2–3 true leaves. After that, the seedlings were transplanted into 40 cm × 40 cm polybags using a one-seedling-per-polybag planting system.

The growing medium consisted of alluvial soil that had been sieved and dried. The growing medium was then placed into 10 kg per polybag. Liming with dolomite at a rate of 4.9 g per polybag was performed two weeks before planting. Water hyacinth-based compost treatment was applied according to the treatment dose and mixed evenly with the soil in the polybags, then incubated for one week before planting.

Compost preparation

The compost was formulated using water hyacinth as the main component. The compost was enriched with cow manure, goat manure, and rice bran to enhance microbial activity and improve the nutrient balance during the composting process. Therefore, the term "water hyacinth-based compost" is used throughout this study to refer to compost in which water hyacinth served as the dominant raw material.

A total of 20 kg of fresh water hyacinth was cut into pieces approximately 5 cm in size. The water hyacinth was then mixed with 3 kg of cattle manure, 3 kg of goat manure, and 4 kg of rice bran. The decomposer used a commercial inoculant (Effective microorganism-EM4). EM stock solution was made by adding 25 mL of EM to one liter of water plus 25 g of white sugar. After mixing and dilution, the solution was sprayed evenly over the composting materials until the moisture content reached approximately 30–40%, as indicated by the formation of a moist aggregate when the material was squeezed by hand.

The compost was fermented for approximately 4 weeks. Every three days, the compost was mixed until mature. Mature compost is characterized by a blackish color, a cool temperature, no pungent odor, and a crumbly texture (Suryani et al., 2024).

PGPR preparation

The PGPR solution was made by fermenting banana stem extract. No additional bacteria or fungi were added. Although specific bacterial isolates were not identified microbiologically, banana stem-based PGPR is commonly reported to contain beneficial rhizosphere bacteria associated with nutrient solubilization and phytohormone production.

The extract was prepared from 250 g of banana pseudostem. It was crushed and soaked in one liter of water for four days. Then, the liquid was filtered to obtain the PGPR starter. The PGPR was made from a mixture of brown sugar (400 g), rice bran (1,000 g), shrimp paste (200 g), and lime powder (100 g) plus 10 L of water. The growing medium was then boiled and cooled. In the final stage, the growing medium and PGPR starter were mixed. The mixture was then fermented for two weeks in a sealed container following the method of Purwaningsih et al. (2023), with modifications, and considered a stock solution.

The microbial population density and taxonomic identity of the PGPR solution were not quantified in this study, as microbiological enumeration (e.g., total plate count) and isolate identification were not performed. As indirect indicators of successful PGPR production, the PGPR solution was monitored for the characteristic sour-fermented odor, gas bubbling, and absence of putrefactive smell during the two-week fermentation period. The method was consistent with the qualitative indicators commonly used to confirm successful PGPR preparations (Purwaningsih et al., 2023).

The lack of quantitative microbial population and identification data is acknowledged as a limitation of this study; consequently, the microbiological composition and cell density of the PGPR used cannot be reported, and this should be addressed through microbial enumeration and identification (e.g., total plate count and 16S rRNA-based identification) in future studies to allow a more mechanistic interpretation of PGPR-related responses.

PGPR was applied starting at 1 to 3 weeks after planting at a frequency of once per week according to the treatment concentration (5, 10, and 15 mL L^{-1}). The solution was applied by watering the growing medium. Each PGPR application used a solution volume of 200 mL to ensure treatment uniformity.

Watering was performed daily in the morning and evening, adjusted according to weather conditions and soil moisture. Plant maintenance included weeding around the plants, as well as pest and disease control using botanical pesticides. Harvesting was conducted 30 days after planting (DAP) based on the criterion that the plants had reached maximum vegetative growth, characterized by fully developed leaves with a fresh green color.

Observation variables

The variables observed in this study included: (1) Plant height, measured from the base of the stem to the tip of the tallest leaf at harvest; (2) Leaf number, counted from all fully expanded leaves at harvest; (3) Fresh weight of the plant shoot, weighed after the plant was harvested and cleaned of adhering soil; (4) Fresh weight of the plant roots, weighed after the roots were cleaned of soil; (5) Leaf greenness index, measured using an SPAD-502 Chlorophyll Meter on the third fully expanded leaf from the shoot apex at harvest; (6) Root volume, measured using the displacement method with a measuring cylinder filled with water.

Data analysis

The data obtained from the observations were analyzed using analysis of variance (ANOVA) at significance levels of 5% and 1%. If the analysis results indicated a significant effect, an honestly significant differences (HSD) test was conducted at the 5% level to determine the differences between treatments. Statistical analysis used statistical software.

Results and discussion

Plant height

The ANOVA results show that the interaction between water hyacinth-based compost and PGPR had a significant effect on plant height (F-calc = 3.4*). Water hyacinth-based compost alone had a highly significant effect on plant height (F-calc = 13.3**), while PGPR showed no significant effect (F-calc = 0.4 ns). The interaction effect and HSD test results are presented in Table 1.

Table 1. Interaction effect of water hyacinth-based compost and PGPR on pak choi plant height

PGPR concentration ($mL\ L^{-1}$)	Compost level (g per polybag)		
	0	50	100
5	19.4ab	19.9ab	19.1ab
10	17.9bc	20.0ab	20.2ab
15	17.2c	20.9a	19.2ab
HSD 5%		2.5	

Note: Values followed by different letters are significantly different at the HSD 5% test.

Based on the HSD test presented in Table 1, application of 50 g per polybag of compost combined with 15 $mL\ L^{-1}$ PGPR resulted in the highest plant height (20.92 cm), which was significantly different from the treatment without compost combined with 15 $mL\ L^{-1}$ PGPR (17.24 cm), but not significantly different from the other treatment combinations. The results also showed different response patterns of plant height to compost application at each PGPR concentration. At 5 $mL\ L^{-1}$ PGPR, increasing the compost level from 0 to 50 g per polybag slightly increased plant height (not significant), but it declined again at 100 g per polybag. These results indicate that the positive role of PGPR becomes evident when compost is added to the growing medium.

The interaction patterns suggest that moderate compost application created a more favorable rhizosphere condition for PGPR activity compared with either no compost or excessive compost application. Compost addition improved soil organic matter, aeration, moisture retention, and nutrient absorption by plants. Without the addition of compost, increasing PGPR concentration seemed to inhibit plant growth, as indicated by lower plant height. Without compost, nutrient limited. This likely explains why increasing PGPR concentration without compost tended to reduce plant height: in the absence of an adequate organic carbon and nutrient substrate, the introduced rhizobacteria and native soil microbes probably competed with plant roots for the limited available nitrogen (microbial immobilization), while the relatively concentrated, unbuffered PGPR solution may also have imposed mild osmotic or phytotoxic stress on roots growing in nutrient-poor soil. In contrast, under moderate compost application (50 g per polybag), PGPR activity became more effective in promoting vegetative growth. However, increasing the compost level to 100 g per polybag did not further increase plant height, indicating that nutrient availability at 50 g per polybag compost was likely sufficient to support optimal vegetative growth. This finding highlights the importance of balanced organic matter application, as excessive doses do not necessarily result in proportional growth improvement.

The significant interaction between water hyacinth-based compost and PGPR on plant height is attributed to a synergistic relationship in the rhizosphere. Water hyacinth-based compost provided organic matter and carbon sources that support PGPR development and activity in the soil. PGPR then accelerates the mineralization of organic matter and increases the availability of nutrients such as nitrogen and phosphorus, and produces growth hormones such as auxin that stimulate cell elongation in the stem. This combination results in more optimal nutrient uptake compared to single treatments, consistent with (Amri et al., 2023; Ridwan et al., 2023).

The availability of nitrogen from organic matter promoted tissue growth. Additionally, improvement of soil physical properties through compost addition increases porosity and water-holding capacity and more efficient nutrient uptake (Zhang et al., 2023; Li et al., 2020). PGPR further enhanced this response through phytohormone production, including auxin and gibberellin, which promote cell elongation and internode elongation, and by increasing nutrient availability through phosphate solubilization and nitrogen fixation (Backer et al., 2018).

Leaf number

The ANOVA result showed that water hyacinth-based compost had a significant effect on the leaf number of pak choi (F-calc = 4.3*), whereas PGPR (F-calc=0.2 ns) and the interaction between water hyacinth-based compost and PGPR (F-calc = 1.1 ns) had no significant effect. These results indicated that leaf formation was primarily influenced by compost application rather than by PGPR or the combined effects of both factors. The means of leaf number as affected by compost and PGPR are presented in Table 2.

Table 2 shows that the compost application increases leaf number compared with the treatment without compost. The application of 100 g per polybag of compost produced the highest leaf number (14.8 leaves), which was significantly higher than the treatment without compost (12.9 leaves), but not significantly different from 50 g per polybag compost. This result indicates that the addition of water hyacinth-based compost improved nutrient availability and supported vegetative growth of pak choi in alluvial soil. In contrast, the application of PGPR did not significantly affect leaf number (Table 2). Although the application of 10 mL L^{-1} PGPR tended to produce a slightly higher leaf number compared with the other concentrations, the difference among treatments was not statistically significant. This result suggests that leaf formation was more strongly influenced by nutrient availability from compost than by microbial stimulation from PGPR.

The number of leaves is strongly influenced by apical meristem activity and nitrogen availability as the primary element for vegetative growth. Nitrogen plays a role in the synthesis of amino acids, proteins, enzymes, and chlorophyll content. Sufficient nitrogen availability increases the rate of cell division and enlargement at the growing point, accelerating the formation of new leaf primordia. Wenno and Sinay (2019) stated that increased nitrogen affects chlorophyll content and leaf number in pak choi. These findings are consistent with the results of previous studies (Amri et al., 2023; Lutfiana et al., 2023). In contrast, PGPR showed no significant effect, as leaf formation is primarily governed by nitrogen availability rather than hormonal stimulation from PGPR, supported by the fact that nitrogen requirements had already been met through compost application (Li et al., 2020; Ridwan et al., 2023). Overall, these findings demonstrate that water hyacinth-based compost plays a more dominant role than PGPR in promoting leaf development of pak choi grown in alluvial soil, primarily through improving nutrient availability and creating more favorable rhizosphere conditions that support sustained vegetative growth.

Water hyacinth-based compost decomposing gradually provides nitrogen continuously, supporting stable apical meristem activity in forming new leaf primordia. Improved rhizosphere conditions also contributed through enhanced root lateral expansion and root hairs, widening the nutrient absorption zone, which directly correlated with increased leaf number (Rahayu et al., 2024; Safitri et al., 2025).

Table 2. The effect of water hyacinth-based compost and PGPR on the leaf number of pak choi

Treatments	Leaf number
Compost dose (g per polybag)	
0	12.9b
50	14.7a
100	14.8a
HSD 5%	1.88
PGPR concentration (mL L^{-1})	
5	14.1
10	14.4
15	13.9
HSD 5%	ns

Note: Values followed by different letters in the same column are significantly different at the HSD 5% test. ns = not significant according to ANOVA at the 5% level.

Shoot fresh weight and root fresh weight

The ANOVA results showed that water hyacinth-based compost had a highly significant effect on fresh shoot weight (F-calc = 25.3^{**}) and fresh root weight (F-calc = 6.5^{**}). In contrast, PGPR and the interaction between water hyacinth-based compost and PGPR had no significant effect on either parameter. The mean of shoot fresh weight and root fresh weight are presented in Table 3.

Table 3. The effect of water hyacinth-based compost and PGPR on fresh shoot weight and fresh root weight of pak choi

Treatments	Shoot fresh weight (g)	Root fresh weight (g)
Compost dose (g per polybag)		
0	36.5b	3.0b
50	62.9a	4.6a
100	57.5a	4.8a
HSD 5%	10.0	1.37
PGPR concentration (mL L^{-1})		
5	53.3	4.3
10	52.1	4.2
15	51.4	3.9
HSD 5%	ns	ns

Note: Values followed by different letters in the same column are significantly different at the HSD 5% test. ns = not significant according to ANOVA at the 5% level.

Table 3 shows that water hyacinth-based compost significantly increased both fresh shoot weight and fresh root weight compared with the control treatment. The application of compost at 50 and 100 g per polybag increased fresh shoot weight from 36.5 g in the control treatment to 62.9 g and 57.5 g, respectively. Similarly, fresh root weight increased from 3.0 g in the control treatment to 4.6 g and 4.8 g following the application of 50 g per polybag and 100 g per polybag, respectively. However, the values obtained at 50 g per polybag and 100 g per polybag were not significantly different for either parameter. Compared with the control treatment, the application of 50 g per polybag increased fresh shoot weight and fresh root weight by 72.3% and 53.3%, respectively, while the application of 100 g per polybag increased the corresponding parameters by 57.5% and 60.0%. In contrast, PGPR application did not significantly affect fresh shoot weight or fresh root weight, as indicated by the relatively similar values across all PGPR concentrations (Table 3).

The increase in fresh shoot weight and fresh root weight indicated that water hyacinth-based compost improved biomass accumulation through enhanced nutrient availability and a better rhizosphere during the vegetative growth phase. Nitrogen promotes chlorophyll formation and photosynthesis; phosphorus facilitates energy transfer and ATP formation; potassium regulates cell turgor pressure and assimilate translocation (Wang et al., 2018). These findings are consistent with Lutfiana et al. (2023), who reported that water hyacinth-based compost significantly increased fresh weight of shoot, and with Yosilia et al. (2025), who demonstrated that the application of organic amendments significantly improves root biomass.

The increase in shoot and root biomass can be explained through the source-sink relationship in plants. Leaves function as the primary source of assimilates through photosynthesis, whereas shoot and root organs act as sinks that utilize assimilates for growth and development. Increased nitrogen availability from compost enhances photosynthetic activity through the formation of structural proteins and metabolic enzymes involved in carbon assimilation, resulting in greater biomass production. At the same time, the incorporation of organic matter improves alluvial soil structure from compacted to more friable conditions, facilitating root penetration, elongation, and nutrient uptake (Utami et al., 2016). Improved rhizosphere conditions also enhance root efficiency in water and nutrient absorption, thereby strengthening the functional relationship between source and sink organs and promoting balanced plant growth (Anggraeny et al., 2025; Rahayu et al., 2024). Furthermore, improved plant water status and cell turgor stability contribute to cell expansion and formation of new tissues, leading to greater biomass accumulation in both shoot and root organs (Kasifah et al., 2026).

The absence of interaction between water hyacinth-based compost and PGPR indicates that pak choi biomass accumulation in response to compost application was relatively independent of PGPR concentration. This suggests that the improvement in nutrient availability and rhizosphere condition resulting from compost application was sufficient to support shoot and root growth, thereby reducing the relative contribution of PGPR under the experimental conditions. In addition, the effectiveness of PGPR is strongly influenced by its ability to establish and function within the rhizosphere environment. When nutrient availability and root growth conditions have already been substantially improved through organic matter addition, the growth response tends to be governed primarily by the direct effects of compost rather than by the combined action of compost and PGPR. Consequently, both factors acted independently, resulting in a non-significant interaction effect on fresh shoot weight and fresh root weight.

The absence of a significant PGPR effect further indicates that biomass accumulation was more strongly influenced by nutrient availability and soil improvement derived from compost application than by microbial inoculation under the experimental conditions. This suggests that the nutrient requirements for vegetative growth had already been sufficiently supplied through compost application, thereby limiting the additional contribution of PGPR to fresh shoot and root biomass development. Overall, these findings demonstrate that water hyacinth-based compost plays a dominant role in increasing shoot and root biomass of pak choi grown in alluvial soil through improvements in nutrient availability, soil physical properties, and rhizosphere conditions that collectively support biomass accumulation and balanced source-sink relationships during vegetative growth.

Leaf chlorophyll content

The ANOVA results showed that water hyacinth-based compost (F-calc = 0.0 ns), PGPR (F-calc = 0.2 ns), and the interaction between water hyacinth-based compost and PGPR (F-calc = 0.7 ns) had no significant effect on leaf chlorophyll content. These results indicated that chlorophyll accumulation remained relatively stable across all treatment levels and was not substantially influenced by compost application or PGPR, or their interaction under the experimental conditions.

The lack of significant differences among treatments indicates that leaf chlorophyll content remained relatively stable across compost doses and PGPR concentrations. This may be attributed to relatively uniform environmental conditions, particularly light intensity and temperature, across the experimental units. Chlorophyll content is regulated not only by nitrogen availability but also by the dynamic balance between chlorophyll synthesis and degradation, which is strongly influenced by environmental factors and the physiological status of the plant. Furthermore, when plant nitrogen requirements are met at a certain level, additional nitrogen from compost does not necessarily lead to a significant increase in chlorophyll content, indicating a physiological limit in leaf chlorophyll accumulation (Safitri et al., 2025; Yosilia et al., 2025).

The absence of a significant interaction between water hyacinth-based compost and PGPR indicates that chlorophyll formation responded similarly across all treatment combinations. This suggests that chlorophyll accumulation was not a limiting physiological process under the experimental conditions and that the nutrient supply provided by compost application was sufficient to maintain normal chlorophyll synthesis. Consequently, the effects of compost and PGPR tended to act independently, resulting in a non-significant interaction effect on leaf chlorophyll content. Overall, these findings indicate that leaf chlorophyll content was relatively stable and was not a major physiological parameter affected by water hyacinth-based compost and PGPR application in pak choi grown on alluvial soil.

Root volume

The ANOVA results showed that water hyacinth-based compost had a highly significant effect on root volume (F-calc = 8.9^{**}), whereas PGPR (F-calc = 0.0^{ns}) and the interaction between water hyacinth-based compost and PGPR (F-calc = 0.7^{ns}) had no significant effect. The effects of compost and PGPR on root volume are presented in Table 4.

Table 4. The effect of water hyacinth-based compost and PGPR on root volume of pak choi

Treatments	Root volume (mL)
Compost dose (g per polybag)	
0	2.9b
50	4.3a
100	4.4a
HSD 5%	1.0
PGPR concentration (mL L^{-1})	
5	3.8
10	4.0
15	3.8
HSD 5%	ns

Note: Values followed by different letters in the same column are significantly different at the HSD 5% test. ns = not significant according to ANOVA at the 5% level.

Table 4 shows that the application of water hyacinth-based compost significantly increased root volume. The application of 50 g per polybag and 100 g per polybag compost increased root volume from 2.9 mL in the control treatment to 4.3 mL and 4.4 mL, respectively. Compared with the control treatment, root volume increased by 48.3% and 51.7% following the application of 50 g per polybag and 100 g per polybag compost, respectively. However, the root volumes obtained at 50 g per polybag and 100 g per polybag were not significantly different, indicating that both compost doses were equally effective in promoting root development in pak choi grown on alluvial soil.

The observed increase in root volume following the application of water hyacinth-based compost suggests that the addition of organic matter improves soil conditions, making them more favorable for root system development. Compost application appears to stimulate lateral root formation and expand the effective root surface area for water and nutrient uptake. Physiologically, phosphorus availability plays a key role in promoting cell division and root tissue differentiation, while nitrogen supports protein synthesis necessary for cell growth. These results are in agreement with previous findings supported by Yosilia et al. (2025) and Anggraeny et al. (2025), who showed that organic matter amendment consistently improves root development.

The non-significant effect of PGPR and its interaction with compost on root volume suggests that when organic matter is sufficient, the plant root system tends to develop optimally without additional hormonal stimulation from PGPR. Root growth is largely influenced by soil physical properties, including porosity, aeration, and moisture availability, which are directly improved through the incorporation of organic matter. Moreover, PGPR effectiveness highly depends on its compatibility with rhizosphere conditions and competition with indigenous microorganisms. Therefore, in growing media already enriched with compost, the role of PGPR becomes less dominant in influencing root volume (Al Hayah et al., 2025; Rahayu et al., 2024).

Overall, these findings indicate that water hyacinth-based compost plays a more important role than PGPR in promoting root system development in pak choi grown on alluvial soil. The increase in root volume reflects an improved capacity of the root system to explore the growing medium and absorb water and nutrients more efficiently. Consequently, enhanced root development may contribute to better plant growth and biomass accumulation, highlighting the potential of water hyacinth-based compost as an effective organic amendment for improving the productivity of pak choi cultivated on alluvial soil.

Conclusions

Water hyacinth-based compost significantly affected plant height, leaf number, shoot fresh weight, root fresh weight, and root volume of pak choi grown on alluvial soil, whereas PGPR generally had no significant effect on the observed parameters. Leaf chlorophyll content was not significantly affected by either water hyacinth-based compost or PGPR. The interaction between water hyacinth-based compost and PGPR was significant only for plant height, while the other parameters responded independently to both factors. The compost application at levels of 50 and 100 g per polybag consistently improved growth and biomass accumulation compared with the control treatment, highlighting the potential of water hyacinth-based compost as an organic amendment for pak choi cultivation on alluvial soil. Further studies using a wider range of compost doses and regression analysis are required to determine the optimum application rate. In addition, as the microbial population and taxonomic identity of the PGPR used in this study were not quantified, future studies incorporating microbial enumeration and identification, together with an untreated (0 mL L^{-1}) PGPR control, are needed to more conclusively determine the general effectiveness of banana stem-based PGPR.

Acknowledgements

The authors thank the Department of Agrotechnology, Faculty of Agricultural Science and Technology, Panca Bhakti University, Pontianak, for providing facilities and supporting this research, and to all parties who have assisted in the execution of this study.

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