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RESEARCH ARTICLE

Growth and yield performance of kale (*Brassica oleracea* L. *var. acephala*) in organic-based soilless substrates under greenhouse conditions

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Abstract

Soil degradation and limited arable land continue to constrain vegetable production in upland areas of the Philippines. This study evaluated the growth and yield performance of kale (*Brassica oleracea* L. var. *acephala*) grown in organic-based soilless substrates under greenhouse conditions. A Completely Randomized Design (CRD) was employed with 5 treatments replicated three times. The treatments consisted of combinations of Processed Chicken Manure (PCM), Carbonized Rice Hull (CRH) and various organic additives, including Vermicompost (VC), Coconut Coir Dust (CCD), Spent Mushroom Compost (SMC) and a control (garden soil + river sand). Growth parameters measured included plant height (PH), root length (RL) and root weight (RW), while yield components comprised leaf length (LL), leaf number (LN), economic yield (EY), biological yield (BY) and harvest index (HI). Results showed that Treatment 1 (PCM + CRH + VC) and Treatment 3 (PCM + CRH + SMC) produced the tallest plants, longest leaves and highest yields. Treatment 2 (PCM + CRH + CCD) promoted superior root development, whereas the control (T_5) recorded the lowest performance in both growth and yield attributes. Organic-based soilless substrates, particularly those enriched with VC or SMC, significantly enhance kale growth and productivity under controlled conditions. The use of these sustainable substrate formulations offers a viable approach to improving vegetable production in land-constrained and ecologically fragile upland environments, supporting the goals of sustainable and climate-resilient agriculture.

Keywords: greenhouse production; kale; organic substrates; soilless culture; sustainable upland agriculture

Introduction

Food security remains a persistent challenge in the Philippines, the 13th most populous country in the world, with a steady population growth rate of approximately 1.44 % per year (1). The increasing demand for food, coupled with the shrinking availability of arable land due to rapid urbanization, environmental degradation and climate change, presents substantial challenges to agricultural productivity (2, 3). The Philippine agricultural sector continues to struggle with declining land quality, water scarcity and pest infestations, all of which are exacerbated by unsustainable farming practices (4, 5). These constraints underscore the urgent need for sustainable, space-efficient and climate-resilient farming approaches to ensure consistent crop yield, nutritional security and enhance rural livelihoods (6, 7).

This need directly aligns with Sustainable Development Goal (SDG) 2 (Zero Hunger), which calls for sustainable solutions to end Hunger and improve food security, particularly through increased agricultural productivity and the income of small-scale food producers. Furthermore, promoting innovative agricultural systems, such as soilless culture, supports SDG 12 (Responsible Consumption and Production) by minimizing natural resource degradation and encouraging efficient food systems (8, 9).

One promising innovation in modern agriculture is soilless culture, a method of cultivating plants without natural soil by using inert or organic substrates combined with nutrient-rich solutions (10, 11). This technique enables precise control of environmental factors such as water availability, pH, nutrient concentration and root-zone temperature, resulting in improved plant health and productivity (12, 13). It also helps prevent soil-borne diseases, reduces the need for pesticides and labor requirements and enables continuous crop production throughout the year—especially when used in conjunction with greenhouse systems (14, 15). Soilless systems are increasingly being adopted in urban and peri-urban settings worldwide, where land is limited but demand for fresh, high-value crops is substantial (16, 17). These environmentally efficient systems also contribute to SDG 13 (Climate Action) by reducing emissions from land degradation and offering low-carbon agricultural alternatives.

Among the many crops suited to soilless cultivation, kale (*Brassica oleracea L. var. acephala)* has gained considerable attention due to its superior nutritional profile and adaptability. Kale is a leafy green vegetable rich in essential vitamins such as A, C and K, as well as minerals like calcium (Ca) and K. It also contains significant levels of dietary fiber, antioxidants and glucosinolates, which contribute to disease prevention and overall health (18, 19).

Owing to its high nutrient density and relatively short growing cycle, kale has been classified as a "superfood" and is increasingly incorporated into health-conscious diets worldwide (20). However, optimal production of kale, particularly in tropical or degraded environments, requires a controlled and efficient cultivation system that can support consistent quality and yield.

In the Philippine context, research on soilless culture remains relatively limited, with existing studies primarily focusing on fast-growing and commonly cultivated leafy greens, such as lettuce, *pechay* and spinach (21, 22). These efforts have helped demonstrate the feasibility of soilless systems in local settings; however, they have not yet extended to high-value, nutrient-dense vegetables like kale, which are increasingly sought after in both domestic and global markets. Despite the recognized health benefits and commercial potential of kale, scientific investigations into its agronomic performance in controlled, soilless environments remain scarce, especially in tropical developing countries like the Philippines. This lack of empirical data limits the formulation of tailored guidelines for optimal kale cultivation using alternative substrates under greenhouse conditions.

Moreover, while developed nations have made significant advancements in hydroponics and other soilless technologies, these innovations have not been widely localized or scaled for use by marginalized rural farming communities in the Philippines. A critical knowledge gap remains concerning the adaptability, sustainability and cost-effectiveness of soilless systems in low-resource, ecologically fragile environments. Thus, this study addresses a dual research gap: the underrepresentation of kale as a model crop in soilless culture research and the scarcity of context -specific investigations suitable for the Philippine highland agriculture sector.

The study is situated in Ifugao, a landlocked province in the Cordillera Administrative Region of northern Luzon, known for its mountainous topography and heritage rice terraces. Agriculture remains the primary livelihood in Ifugao, but local farmers contend with declining soil fertility, erosion, steep slopes and limited access to modern farming technologies (23). These biophysical and socio-economic constraints often restrict productivity and the diversification of crop options. Nonetheless, the long-standing traditions in resource-efficient farming of Ifugao, including its globally recognized indigenous agroecological knowledge, make it an ideal location for piloting soilless agricultural systems. The use of greenhouse-based soilless cultivation presents a timely and adaptive strategy, particularly for off-season and high-value vegetable production, offering a potential pathway toward food security, improved nutrition and climate-resilient agriculture in upland communities.

This study specifically aimed to evaluate organic-based soilless culture technologies for the production of kale under controlled greenhouse conditions in a rural upland setting. The research involved assessing the performance of various locally sourced organic substrate combinations, focusing on their effects on key indicators of plant growth, namely, height, root development and biomass, as well as yield parameters such as LL, number and total productivity. While the primary emphasis was on growth and yield optimization, the study also considered the economic viability of each treatment to determine its potential for scalable and sustainable application. Ultimately, the findings aim to contribute to the advancement of sustainable agricultural practices in marginalized, land-constrained areas, offering a replicable production model suited for smallholders and upland farmers. This aligns with the goals of SDG 15 (Life on Land), which advocates sustainable land use, ecosystem restoration and the promotion of resilient farming systems in ecologically vulnerable regions. This research aimed to investigate the growth and yield responses of kale to various organic-based soilless substrate treatments under greenhouse conditions.

Specifically, this study aimed to evaluate the growth characteristics of kale plants, including PH, RL and RW, under various combinations of soilless substrates. Moreover, the study aimed to compare the yield components of kale grown in different soilless substrates, including LL, number of leaves, EY, BY and HI. Ultimately, the study aims to determine the most effective soilless substrate treatment that promotes optimal vegetative growth and maximum yield in kale production.

Materials and Methods

Experimental site and design

The experiment was conducted in a greenhouse at Mrs. Aquilina Saguilot's farm, located in Ifugao Province, Philippines (16° 48′ N, 121° 04′ E), characterized by a tropical highland climate. Fifteen plots, each measuring 1 m × 5 m, were established. The experiment employed a Completely Randomized Design (CRD) with three replications per treatment due to space limitations within the greenhouse facility. Although three replications were sufficient for treatment comparison, future studies are recommended to include at least four replications to increase degrees of freedom and improve statistical power.

Treatments and substrates

The experiment tested five treatments composed of the following substrate mixtures:

T_1 – Processed Chicken Manure (PCM) + Carbonized Rice Hull (CRH) + Vermicompost (VC)

T_2 – PCM + CRH + Coconut Coir Dust (CCD)

T_3 – PCM + CRH + Spent Mushroom Compost (SMC)

T_4 – PCM + CRH

T_5 – Garden Soil + River Sand (Control)

All organic substrates were sourced locally from Ifugao and Nueva Vizcaya, Philippines. Substrate mixtures for T_1–T_3 followed a 1:1:1 volume ratio, T_4 used a 1:1 ratio and the control treatment (T_5) used a 3:1 garden soil-to-river sand ratio.

Elemental composition of organic substrates

The chemical composition of the organic inputs was based on literature reports of similar locally sourced materials. Processed chicken manure is typically rich in macronutrients, containing approximately 2.5 %–3.0 % nitrogen (N), 2.0 %–2.5 % phosphate (P_2O_5) and 1.5 %–2.0 % potash (K_2O), along with significant organic matter (21). Vermicompost contains approximately 1.5 %–2.0 % N, 0.5 %–1.0 % P and 1.0 %–1.5 % K, with high microbial activity that enhances nutrient mineralization (27). Spent mushroom compost averages 1.2 % N, 0.8 % P and 1.0 % K. At the same time, CCD and CRH primarily serve as structural substrates with minimal nutrient content but excellent aeration and water-holding properties (24, 25).

The estimated nutrient composition of each substrate combination is summarized in Table 1, adapted from the references cited. This elemental information clarifies the nutrient potential of the substrates and supports the interpretation of growth and yield differences among treatments.

Planting procedure

The experiment was conducted from March to May 2024, coinciding with the dry season in the Cordillera region, to minimize the effects of excessive rainfall. Three five-gram packs of kale seeds (Model T) were directly sown into the designated plots. After emergence, seedlings were thinned to ensure uniform spacing and optimal growth. Transplanting was not required because of the direct seeding method.

Cultural management

Kale plants were irrigated regularly to maintain consistent moisture levels, thereby avoiding water stress symptoms such as yellowing or leaf dropping. An organic fertilizer known as Fermented Plant Juice (FPJ) was applied at a concentration of 10 mL per 1.75 L of water on a weekly basis, starting two weeks after emergence and continuing until one week prior to harvest. Plants were regularly monitored for pests and diseases and preventive cultural practices were applied as necessary.

Statistical analysis

Data were collected to evaluate the growth performance and yield traits of kale grown under various soilless substrate conditions. Growth metrics included maturity, recorded as days after sowing (DAS); PH (cm); RL (cm); and RW (g). Yield metrics encompassed LL (cm); LN; EY (shoot weight (SW), g); BY (SW and RW, g); and HI as a percentage. Collectively, these measures presented a complete assessment of vegetative development, biomass accumulation and biomass partitioning efficiency in kale grown in greenhouse soilless culture.

Data were subjected to one-way Analysis of Variance (ANOVA) following a CRD to determine the significance of differences among treatments. When significant F-values were obtained ($p < 0.05$), means were compared using Tukey's Honest Significant Difference (tHSD) test o identify specific pairwise differences among treatments. Descriptive statistics, including mean and standard deviation, were computed for all measured growth and yield parameters. All statistical analyses were performed using SPSS version 26.0.

Results and Discussion

Growth characteristics of kale plants: plant height, root length and root weight under various soilless substrate combinations

Table 2 and Fig. 1–3 summarize the kale growth parameters across five soilless substrate treatments (T_1 to T_5). The Tukey HSD test at $p < 0.05$ reveals statistical differences among treatments for each parameter.

Plant height

Plant height varied from 38 cm in the T5 group to 48 cm in the T_1 and T_3 groups. T_1 and T_3 samples had the highest plants and there was no significant difference. T_5 plants were significantly shorter.

These findings are consistent with other research that emphasizes the importance of the quality and nutrient availability of the substrate for kale seedlings. A study found that seedlings grown in substrates with higher water-holding capacity and nutrient content exhibited higher aerial growth, as evidenced by increased PH (26). The poorer substrates, or those with lower water and nutrient holding capacities, which might have stressed the seedlings or resulted in a lack of resource availability, such as T5 in this study, often elevate physiological stress and cause the plant to be shorter. It was also observed from another study that significant differences existed in kale seedlings and that seedlings grown in more aerated and nutrient-balanced media were larger and, therefore, more suitable for transplantation (27). These effects arise because good media structure facilitates root growth and nutrient absorption necessary for shoot elongation.

Root length

Root length was longest in T_2 (36 cm) and shortest in T_5 (14 cm), with T_1 and T_3 both at 32 cm. T_2 and T_4 showed relatively better root development than T_1 and T_3, but no significant difference in RL between T_2 and T_4.

Root system development is critical for plant vigor and nutrient uptake. Adequate aeration, moisture and nutrient availability in the substrate promote root elongation. A study reported that soilless substrates with balanced humidity and aeration encourage root growth in curly kale, supporting increased RL similar to observations in T_2 and T_4 (26). The markedly reduced RL in T_5 indicates substrate limitations in supporting healthy root expansion.

Table 1. Elemental composition and functional characteristics of organic substrates used in soilless kale production

Substrate	N (%)	P (%)	K (%)	Key functional role
Processed chicken manure	2.5–3.0	2.0–2.5	1.5–2.0	Provides macronutrients essential for vegetative growth
Vermicompost	1.5–2.0	0.5–1.0	1.0–1.5	Enhances microbial activity and nutrient mineralization
Spent mushroom compost	1.2	0.8	1.0	Improves soil fertility and organic matter content
Coconut coir dust	< 0.5	< 0.2	< 0.3	Enhances water-holding capacity and root aeration
Carbonized rice hull	< 0.5	< 0.1	< 0.2	Improves substrate aeration and drainage efficiency

Note: Nutrient composition values are approximate ranges based on literature sources (21, 24–27). These estimates represent typical nutrient concentrations of locally sourced materials and are used to interpret the effects of treatment on kale growth and yield.

Table 2. Growth characteristics of kale under different soilless substrate treatments

Treatments	Plant height (cm)			Root length (cm)			Root weight (g)		
	Mean	SD	Letter	Mean	SD	Letter	Mean	SD	Letter
T_1	48	1.597	a	32	1.083	a	2.5	0.294	a
T_2	46	0.947	b	36	1.531	a	3.2	0.249	a
T_3	48	1.017	a	32	1.050	b	2.5	0.227	b
T_4	46	0.830	b	34	1.619	b	3.0	0.294	b
T_5	38	1.287	c	14	1.639	c	1.1	0.203	c

Note: Values represent the mean ± standard deviation (SD) of three replications (n = 3) analyzed under a completely randomized design (CRD). Means followed by different letters within a column differ significantly at the 5 % probability level ($p < 0.05$) according to Tukey's honest significant difference (HSD) test. Observations were recorded 60 days after sowing.

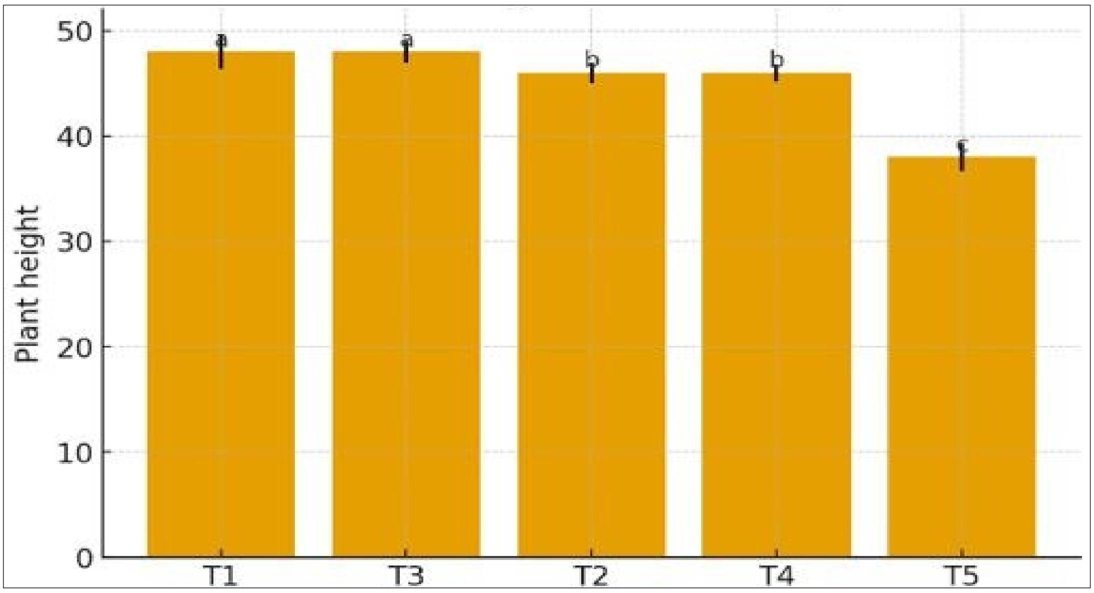

Fig. 1. Effect of organic-based soilless substrates on plant height of kale under greenhouse conditions (mean ± SD, n = 3). Bars with the same letter are not significantly different at $p < 0.05$.

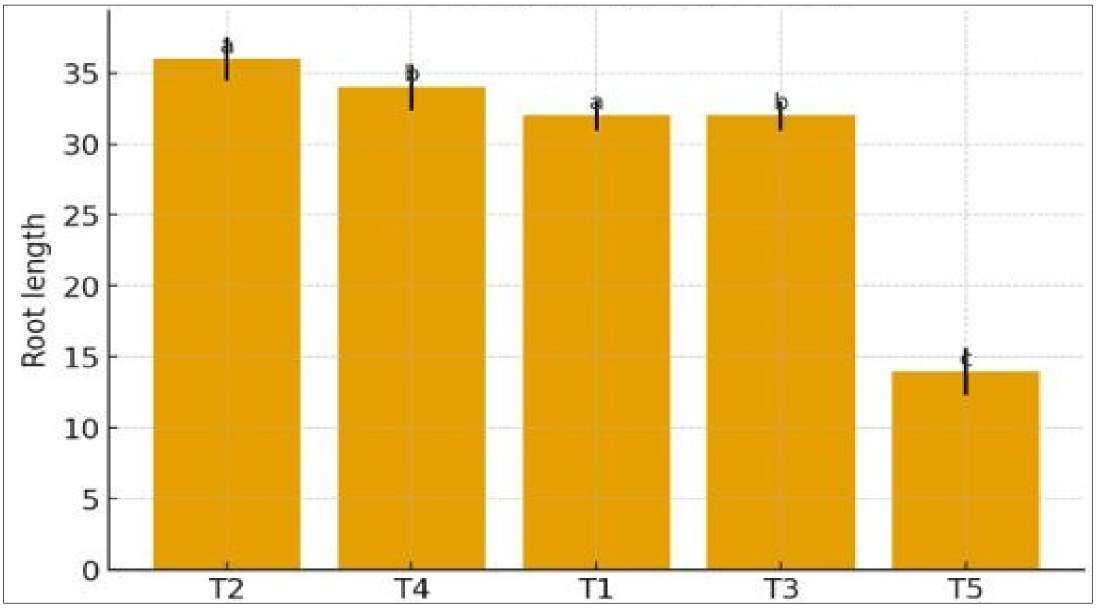

Fig. 2. Effect of organic-based soilless substrates on root length of kale under greenhouse conditions (mean ± SD, n = 3). Bars with the same letter are not significantly different at $p < 0.05$.

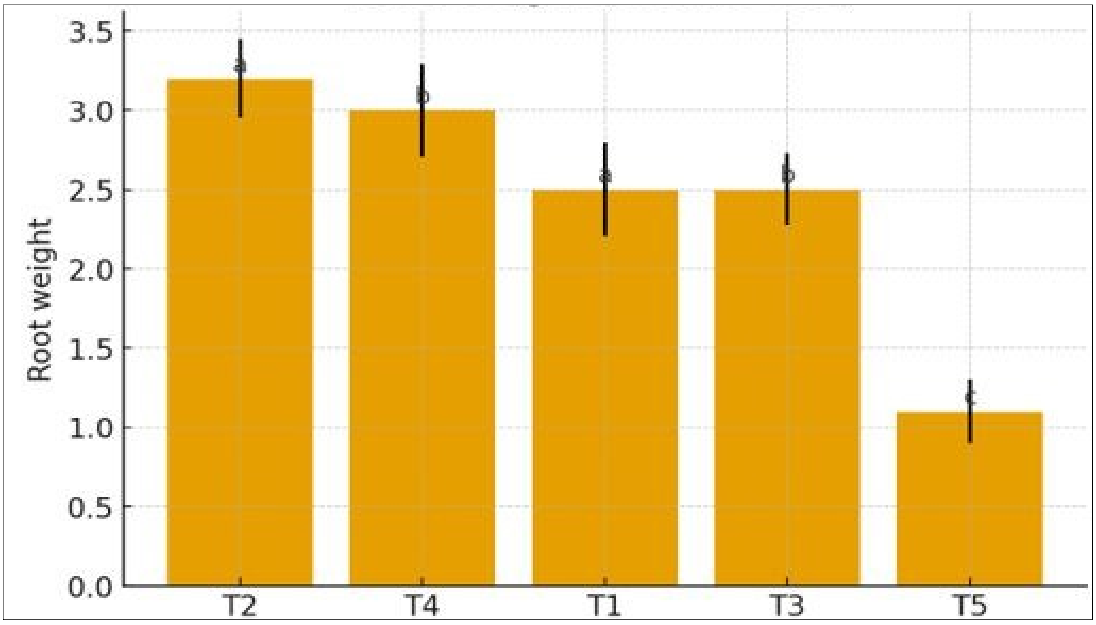

Fig. 3. Effect of organic-based soilless substrates on root weight of kale under greenhouse conditions (mean ± SD, n = 3). Bars with the same letter are not significantly different at $p < 0.05$.

Root weight

Root weight ranged from 1.1 g (T_5) to 3.2 g (T_2). T_1 and T_2 had the highest root biomass, indicating more robust and possibly denser root systems, while T_5 recorded significantly lower RW.

Root biomass has been shown to be positively correlated with substrate fertility and water retention capacity (26). Media with sufficient organic matter and nutrient availability promote greater root mass accumulation, which drives improved nutrient and water absorption capacity, supporting overall plant growth. The lower root biomass in T_5 might be due to inadequate substrate properties limiting root development and function, as also noted in previous research on soilless cultivation (27, 28).

The differences in kale growth characteristics across soilless substrate treatments highlight the importance of substrate properties, such as water retention, aeration and nutrient availability, in supporting optimal PH and root development.

T_1, T_2 and T_4 demonstrated favorable growth attributes, which correspond with enhanced substrate quality and fertility, consistent with previous scientific findings on kale growth in soilless media (26–28). The consistently lower values of T_5 emphasize the critical role of an adequate growing medium.

Comparison of the yield components of kale grown in different soilless substrates in terms of leaf length, leaf number, economic yield, biological yield and harvest index

Table 3 and Fig. 4-8 present key yield parameters of kale plants grown in different soilless substrate treatments as assessed by LL, LN, EY, BY and HI. The results indicate significant variation among treatments in most parameters, except for the HI, which shows less variation with shared statistical grouping (indicated by the same letter "a" or "b"). Tukey HSD test was used to determine significant differences at $p < 0.05$.

Leaf length and leaf number

Leaf length ranged from 18 cm (T_5) to 32 cm (T_1 and T_3), with the control (T_5) producing the smallest leaves, which were significantly smaller than those of the other treatments. The number of leaves varied between 6 and 8 per plant, with T_5 again exhibiting the lowest count. These findings are consistent with studies showing that substrate composition and nutrient availability directly influence leaf morphological traits in *Brassica* species.

The superior performance of T_1 (PCM + CRH + VC) and T_3 (PCM + CRH + SMC) can be attributed to the higher nutrient content of VC and SMC. Previous elemental analyses have shown that VC typically contains 1.5 %–2.0 % N, 0.5 %–1.0 % P and 1.0 %–1.5 % K, while SMC averages around 1.2 % N, 0.8 % P and 1.0 % K (24–26). In contrast, CRH and CCD are primarily structural substrates with limited nutrient contribution, though they enhance aeration and water retention (25). The observed leaf elongation and greater LN in T_1 and T_3 thus reflect the synergistic effects of nutrient-rich and physically favorable substrates.

These results align with the findings of another study, which demonstrated that nutrient-enriched media containing peat and coco coir significantly increased leaf expansion and biomass accumulation in kale (28). Similarly, it was also reported that organic compost supplementation improved vegetative growth by enhancing substrate fertility and cation exchange capacity (26). The smaller leaf size and reduced leaf count in the control treatment (T_5) likely indicate nutrient limitation and suboptimal root-zone conditions.

Economic yield and biological yield

Economic yield (marketable leaf biomass) ranged from 48.0 g (T_5) to 80.0 g (T_1), with T_1 achieving the highest significant yield. Biological yield (total biomass) followed a similar trend, ranging from 49.1 g (T_5) to 82.5 g (T_1). T_1, T_3 and T_2 outperformed T_4 and the control, indicating that substrates enriched with VC, SMC, or CCD promoted superior yield performance.

These results are consistent with the outcome of a previous study, which found that the inclusion of VC tea or organic amendments significantly increased kale yield in soilless systems (29). Another study observed that appropriate nutrient management and substrate optimization improved the biological efficiency and shoot biomass of ornamental kale (30). The improved yield in this study is further supported by the known nutrient richness of PCM, which contains approximately 2.5 %–3.0 % N, along with appreciable P and K (21). The presence of these essential macronutrients likely contributed to vigorous shoot development and greater photosynthetic productivity.

While direct nutrient analysis of kale tissues was not performed, previous research supports the correlation between enhanced growth and improved foliar nutrient content. Another study reported that kale grown in nutrient-rich soilless substrates accumulated higher concentrations of N, K and magnesium (Mg) than plants grown in soil-based systems (31). Likewise, it was also observed that there was an increase in chlorophyll and mineral content in kale leaves cultivated on compost-based media (26). Hence, the superior yields observed in T_1 and T_3 may also reflect the improved nutritional quality of kale produced in these treatments.

Harvest index

Harvest index values were uniformly high across treatments (95.5 %–97.75 %) and did not differ significantly in most cases. This indicates that despite variations in yield magnitude, the proportion of EY relative to total biomass remained stable. A high HI is desirable as it reflects efficient biomass allocation to edible plant parts. A separate study similarly reported high and stable harvest indices for kale under various cultivation systems, suggesting consistent partitioning of photosynthates to leaves, even under variable environmental or nutrient conditions (32).

Overall, the composition of the soilless substrate had a significant influence on kale yield and its components. Treatments T_1 (PCM + CRH + VC) and T_3 (PCM + CRH + SMC) yielded the longest

Table 3. Yield components of kale under different soilless substrate treatments

Treatments	Leaf length (cm)			Leaf number (pcs)			Economic yield (g)			Biological yield (g)			Harvest index (%)		
	mean	sd	letter	mean	sd	letter	mean	sd	letter	mean	sd	letter	mean	sd	letter
T_1	32	1.017	a	8	0.910	a	80.0	1.339	a	82.5	1.503	a	97.00	1.050	a
T_2	30	1.017	a	8	1.017	a	74.5	1.009	b	77.7	1.725	b	96.20	1.270	a
T_3	32	1.174	b	8	0.910	a	79.0	1.287	b	81.5	1.676	a	97.00	1.339	a
T_4	28	1.203	c	7	0.928	b	75.0	1.203	c	78.2	1.846	b	95.50	1.358	b
T_5	18	1.083	d	6	0.830	c	48.0	1.531	d	49.1	1.242	c	97.75	0.998	a

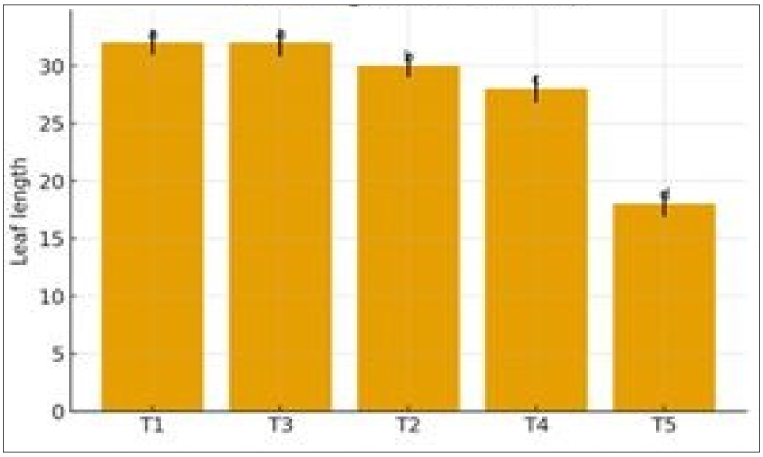

Fig. 4. Effect of organic-based soilless substrates on leaf length of kale under greenhouse conditions (mean ± SD, n = 3). Bars with the same letter are not significantly different at $p < 0.05$.

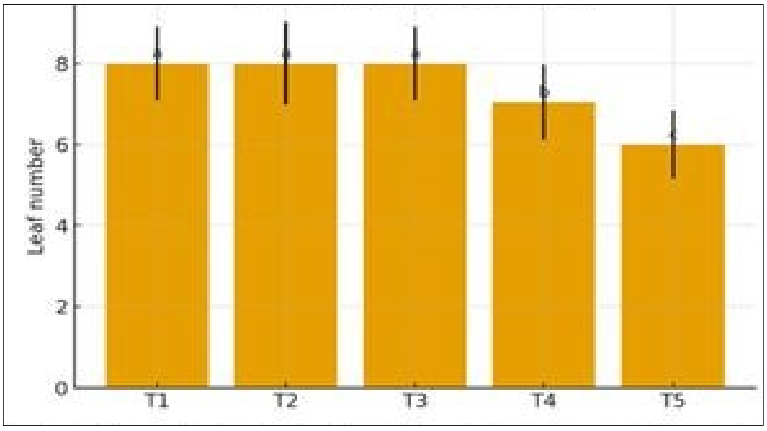

Fig. 5. Effect of organic-based soilless substrates on leaf number of kale under greenhouse conditions (mean ± SD, n = 3). Bars with the same letter are not significantly different at $p < 0.05$.

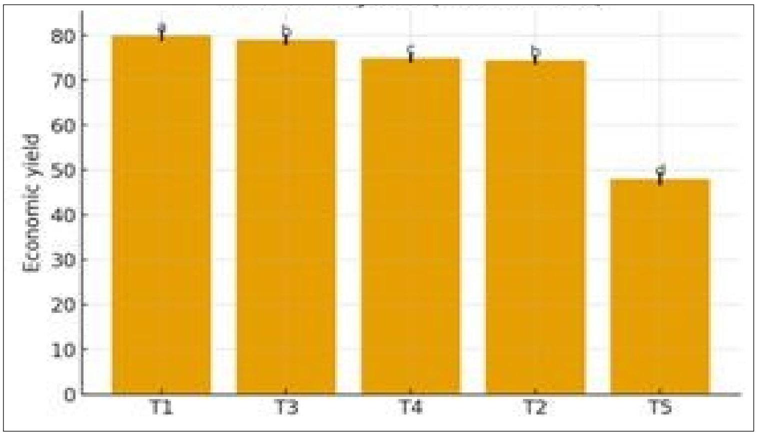

Fig. 6. Effect of organic-based soilless substrates on economic yield of kale under greenhouse conditions (mean ± SD, n = 3). Bars with the same letter are not significantly different at $p < 0.05$.

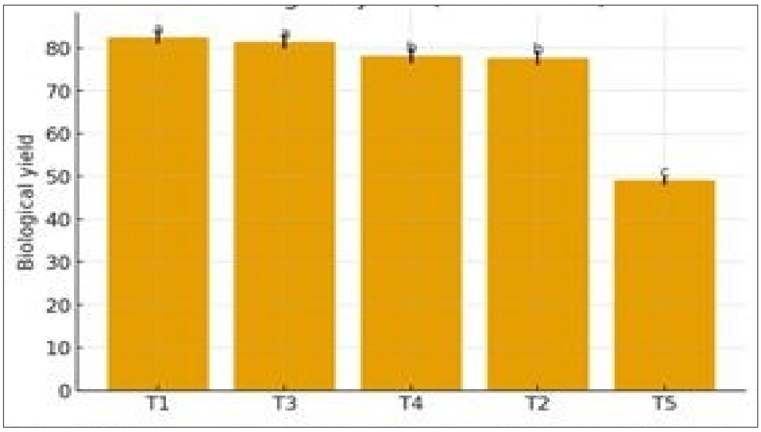

Fig. 7. Effect of organic-based soilless substrates on biological yield of kale under greenhouse conditions (mean ± SD, n = 3). Bars with the same letter are not significantly different at $p < 0.05$.

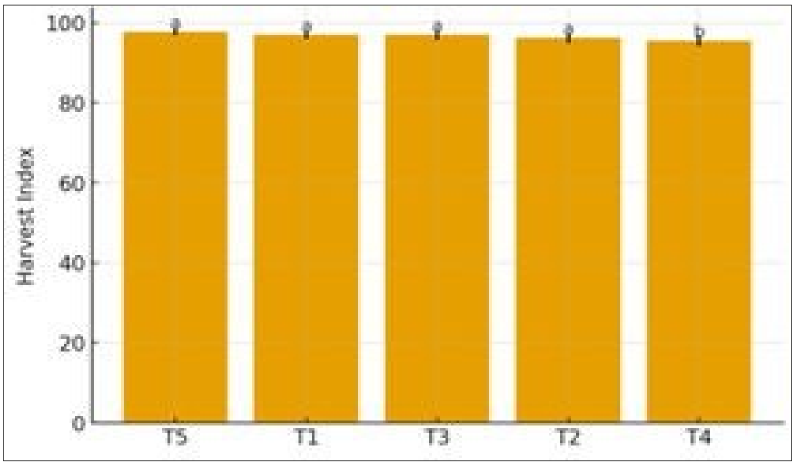

Fig. 8. Effect of organic-based soilless substrates on harvest index of kale under greenhouse conditions (mean ± SD, n = 3). Bars with the same letter are not significantly different at $p < 0.05$.

leaves, greatest LN and highest biomass production, owing to their balanced nutrient supply and favorable substrate properties. The integration of nutrient-rich organic amendments not only enhanced growth and yield but also likely improved the nutritional status of the harvested kale. These results underscore the potential of organic-based soilless systems to enhance both productivity and produce quality, aligning sustainable agriculture goals for resource-efficient vegetable production.

Most effective soilless substrate treatment that promotes optimal vegetative growth and maximum yield in kale production

The most effective soilless substrate treatment that promotes optimal vegetative growth and maximum yield in kale production is T_1. This is based on a comparative analysis of growth characteristics (PH, RL and RW) and yield components (LL, LN, EY and BY) across the treatments. T_1 consistently showed superior or statistically highest values in key growth parameters: (a) Highest PH (48 cm); (b) High RL (32 cm) and RW (2.5 g) comparable with other top treatments; (c) Greatest LL (32 cm), highest EY (80.0 g) and highest BY (82.5 g); and (d) A stable, high HI (97.00 %), indicating efficient biomass allocation.

While T_2 and T_3 also performed well in many parameters, T_1 holds consistent superiority or equivalence across most growth and yield indicators. T_5 was distinctly the least effective across all metrics.

The effectiveness of T_1 likely stems from the balanced nutrient availability, optimal moisture retention and adequate aeration provided by the substrate composition, which are known critical factors that enhance kale growth and productivity in soilless systems (25, 28, 31, 32). In practical terms, selecting substrate formulations with characteristics similar to those of T1 will maximize kale vegetative growth and yield in soilless cultivation, making it the most recommended choice for growers seeking high productivity and quality.

Conclusion

The composition of soilless substrate significantly affects the growth and yield of kale under greenhouse conditions. Organic-based mixtures, particularly T_1 (PCM + CRH + VC), T_2 (PCM + CRH + CCD) and T_3 (PCM + CRH + SMC), consistently produced greater pH, improved root growth and higher LN and biomass yield than other formulations. These results highlight the importance of maintaining a balanced nutrient regime, effective moisture retention and adequate substrate aeration in optimizing kale production. The control treatment (T_5: Garden Soil + River Sand) resulted in markedly lower growth and yield, indicating that traditional soil–sand media are less suitable for controlled cultivation. However, the relatively stable HI across treatments suggests efficient allocation of biomass to edible leaves, even under nutrient limitations. The superior performance of T_1 highlights its potential as a practical, sustainable substrate for upland and resource-limited farmers seeking to improve productivity. Beyond localized greenhouse production, organic-based soilless systems support circular agricultural economies by utilizing regionally available materials, such as VC, SMC and CRH. These practices reduce reliance on synthetic fertilizers, lower costs and promote sustainable land use, thereby contributing to the attainment of SDGs 2 (Zero Hunger) and 15 (Life on Land). Future research should focus on optimizing nutrient formulations, evaluating the reuse potential of organic substrates and assessing the nutritional quality of kale produced under different treatments. Collaborative research and farmer training are also recommended to promote the wider adoption of sustainable soilless cultivation technologies in the Philippines and other upland farming communities. Moreover, subsequent studies should include a minimum of four replications to enhance statistical precision, improve the reliability of treatment comparisons and strengthen the validity of experimental results under greenhouse conditions.

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Authors' contributions

MPB was solely responsible for the conceptualization of the study, designing the experiment, data collection and analysis and composition of the manuscript. The author read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Author do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process: The author affirms that generative AI tools, specifically Perplexity, Jenni AI, QuillBot and Grammarly, were used to assist in the writing, editing and refinement of this article. These tools were employed solely to enhance the clarity, structure and academic tone of the text. The author maintains full responsibility for the content, interpretation of results, critical analysis and conclusions presented in the article. No generative AI was used to generate research data, analysis, or scientific claims.

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