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Effect of sustainable hydroponic substrates on biomass and essential oil of *Plectranthus amboinicus*

Efecto de sustratos hidropónicos sostenibles sobre biomasa y aceite esencial de *Plectranthus amboinicus*

Efeito de substratos hidropônicos sustentáveis sobre biomassa e óleo essencial de *Plectranthus amboinicus*

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ABSTRACT

The effect of four hydroponic substrates on the growth kinetics, biomass accumulation and essential oil yield of *Plectranthus amboinicus* (Lour.) Spreng. was evaluated under tropical conditions in Puerto López, Colombia. A completely randomized design was used with four treatments: river sand (T1), coconut fiber + rice husk mixture 1:1 (T2), rice husk (T3), and pure coconut fiber (T4), with five replicates. Height growth fitted a logistic model (R^2 > 0.99), and T2 and T4 showed the highest maximum growth rates (5.88 and 5.53 cm/week). At the end of the cycle, T4 recorded the highest total fresh biomass (880.00 g/plant), fresh leaf biomass (554.22 g/plant), and dry leaf biomass (66.62 g/plant). The highest essential oil yield obtained by microwave-assisted hydrodistillation was observed in T4 (0.748 % on a dry basis; 0.090 % on a fresh basis), followed by T2 (0.577 %), T3 (0.434 %), and T1 (0.320 %). Under the evaluated conditions, coconut fiber favored biomass accumulation and essential oil yield, making it a promising substrate for tropical hydroponic systems of *P. amboinicus*.

key words: coconut fiber, essential oil, hydrodistillation, growth kinetics, logistic model, Cuban oregano

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RESUMEN

Se evaluó el efecto de cuatro sustratos hidropónicos sobre la cinética de crecimiento, acumulación de biomasa y rendimiento de aceite esencial de *Plectranthus amboinicus* (Lour.) Spreng. bajo condiciones tropicales en Puerto López, Colombia. Se utilizó un diseño completamente al azar con cuatro tratamientos: arena de río (T1), mezcla fibra de coco + cascarilla de arroz 1:1 (T2), cascarilla de arroz (T3) y fibra de coco pura (T4), con cinco repeticiones. El crecimiento en altura se ajustó a un modelo logístico ($R^2 > 0.99$), y T2 y T4 presentaron las mayores tasas máximas de crecimiento (5.88 y 5.53 cm/semana). Al final del ciclo, T4 registró la mayor biomasa fresca total (880.00 g/planta), biomasa foliar fresca (554.22 g/planta) y biomasa foliar seca (66.62 g/planta). El mayor rendimiento de aceite esencial extraído por hidrodestilación asistida por microondas se obtuvo en T4 (0.748 % en base seca; 0.090 % en base fresca), seguido de T2 (0.577 %), T3 (0.434 %) y T1 (0.320 %). Bajo las condiciones evaluadas, la fibra de coco favoreció la acumulación de biomasa y el rendimiento de aceite esencial, por lo que constituye un sustrato promisorio para sistemas hidropónicos tropicales de *P. amboinicus*.

palabras clave: aceite esencial, cinética de crecimiento, fibra de coco, hidrodestilación, modelo logístico, orégano brujo

RESUMO

Avaliou-se o efeito de quatro substratos hidropônicos sobre a cinética de crescimento, acumulação de biomassa e rendimento de óleo essencial de *Plectranthus amboinicus* (Lour.) Spreng. em condições tropicais em Puerto López, Colômbia. Utilizou-se delineamento inteiramente casualizado com quatro tratamentos: areia de rio (T1), mistura fibra de coco + casca de arroz 1:1 (T2), casca de arroz (T3) e fibra de coco pura (T4), com cinco repetições. O crescimento em altura ajustou-se a um modelo logístico ($R^2 > 0.99$), e T2 e T4 apresentaram as maiores taxas máximas de crescimento (5.88 e 5.53 cm/semana). Ao final do ciclo, T4 registrou a maior biomassa fresca total (880.00 g/planta), biomassa foliar fresca (554.22 g/planta) e biomassa foliar seca (66.62 g/planta). O maior rendimento de óleo essencial obtido por hidrodestilação assistida por micro-ondas foi observado em T4 (0.748 % em base seca; 0.090 % em base fresca), seguido de T2 (0.577 %), T3 (0.434 %) e T1 (0.320 %). Nas condições avaliadas, a fibra de coco favoreceu a acumulação de biomassa e o rendimento de óleo essencial, constituindo um substrato promissor para sistemas hidropônicos tropicais de *P. amboinicus*.

palavras chave: cinética de crescimento, fibra de coco, hidrodestilação, modelo logístico, óleo essencial, orégano cubano

INTRODUCTION

The cultivation of aromatic and medicinal plants has gained increasing relevance in Latin America due to its agroindustrial potential and the growing demand for essential oils in the pharmaceutical, cosmetic, and food sectors (FAO, 2019; Ministerio de Agricultura y Desarrollo Rural, 2021). Among the species of greatest interest, *Plectranthus amboinicus* (Lour.) Spreng., commonly known as Cuban oregano or Indian borage, stands out for its rapid growth, adaptability to tropical conditions, and content of secondary metabolites of biological interest (Arumugam et al., 2016; Monzote et al., 2020; Antonio-Gutiérrez et al., 2023).

In Colombia, the use of aromatic species represents an opportunity to diversify agricultural systems, contributing to productive sustainability and the strengthening of the rural economy (FAO, 2021). Hydroponic systems emerge as a clean and efficient technology that optimizes the use of water and nutrients, reduces dependence on soil conditions, and allows controlled and continuous production (Gruda, 2019; Barrett et al., 2016). Hydroponics also makes it possible to evaluate alternative substrates of agroindustrial origin, such as coconut fiber and rice husk, which can contribute to the sustainability of productive systems (Signore et al., 2023; Tuckeldoe et al., 2023).

The type of substrate in soilless systems significantly influences plant development by modifying water retention, root aeration, and nutrient availability (Abad et al., 2001; Gruda, 2019). Recent studies show that substrate selection can affect biomass and the accumulation of secondary metabolites in species of the Lamiaceae family (Lam et al., 2020; Ryu et al., 2023). However, there is scarce information on the response of *P. amboinicus* to sustainable hydroponic substrates under tropical conditions of the Colombian Orinoquia.

The hypothesis was proposed that substrates with higher water retention capacity, particularly coconut fiber, would favor a higher growth rate, biomass accumulation, and essential oil yield in *P. amboinicus* under tropical hydroponic conditions. The objective of the study was to evaluate the effect of four hydroponic substrates on the growth kinetics, aerial biomass, and essential oil yield of *P. amboinicus* cultivated under tropical conditions of the Colombian Orinoquía.

MATERIALS AND METHODS

experimental design

The experiment was carried out in Puerto López (Meta, Colombia; 4°05'N, 72°57'W; 254 m a.s.l.), in a protected environment with plastic covering and natural ventilation, between October 2025 and January 2026. A completely randomized design (CRD) was used with four treatments: T1 = washed river sand; T2 = coconut fiber + rice husk mixture (1:1 v/v); T3 = rice husk; T4 = pure coconut fiber. Each treatment had five replicates, for a total of 20 experimental units. The experimental unit corresponded to a plant grown individually in a 6 L double-layer bag.

plant material

Apical cuttings of *P. amboinicus* of 10 cm length and 3–4 nodes from healthy mother plants were used. The cuttings were disinfected with 1 % sodium hypochlorite for 5 min, rinsed with distilled water, and established in the previously moistened substrates. The physicochemical properties of the substrates were determined according to Abad et al. (2001): pH 6.0–6.5; EC 1.2–1.8 dS/m; density 0.15–0.35 g/cm^3; water retention 55–75 %.

agronomic management

Hoagland and Arnon (1950) No. 1 nutrient solution was used, modified by replacing the original ferric tartrate with chelated iron (Fe-EDTA) according to Jacobson (1951). The detailed composition of salts, quantities for preparation of 1000 L, and final elemental concentrations are presented in Tables 1 and 2. pH was adjusted between 5.8–6.2 and EC between 1.6–1.8 dS/m. Irrigation was applied every 24 h to field capacity, with free drainage. The average temperature was 30 ± 2 °C and relative humidity 75 ± 5 %. The total duration of the cycle was 115 days after transplanting (dat).

Table 1. Salts and quantities for the preparation of 1000 L of No. 1 Hoagland and Arnon (1950) modified nutrient solution.

Compound	Chemical formula	Quantity for 1000 L
Macronutrients		
Potassium nitrate	KNO_3	505.5 g
Calcium nitrate tetrahydrate	$Ca(NO_3)_2{\cdot}4H_2O$	1180.8 g
Monopotassium phosphate	KH_2PO_4	136.1 g
Magnesium sulfate heptahydrate	$MgSO_4{\cdot}7H_2O$	492.9 g
Micronutrients (prepare 1 L stock; add 1 L per 1000 L final solution)		
Boric acid	H_3BO_3	2.86 g/L stock
Manganese chloride tetrahydrate	$MnCl_2{\cdot}4H_2O$	1.81 g/L stock

Compound	Chemical formula	Quantity for 1000 L
Zinc sulfate heptahydrate	$ZnSO_4{\cdot}7H_2O$	0.22 g/L stock
Copper sulfate pentahydrate	$CuSO_4{\cdot}5H_2O$	0.08 g/L stock
Sodium molybdate dihydrate	$Na_2MoO_4{\cdot}2H_2O$	0.028 g/L stock
Chelated iron (Fe-EDTA)†	$C_{10}H_{12}FeN_2O_8$	5.0 g/L stock

† Modification: the original ferric tartrate of Hoagland and Arnon (1950) was replaced by chelated iron (Fe-EDTA) according to Jacobson (1951). pH adjusted to 5.8–6.2; EC 1.6–1.8 dS/m.

Table 2. Final elemental concentration of each mineral in the nutrient solution.

Element	Source	Final conc. (ppm)
Macronutrients		
Nitrogen (N)	KNO_3 + $Ca(NO_3)_2$	210.1
Phosphorus (P)	KH_2PO_4	31.0
Potassium (K)	KNO_3 + KH_2PO_4	234.6
Calcium (Ca)	$Ca(NO_3)_2{\cdot}4H_2O$	200.4
Magnesium (Mg)	$MgSO_4{\cdot}7H_2O$	48.6
Sulfur (S)	$MgSO_4{\cdot}7H_2O$	64.1
Micronutrients		
Iron (Fe)†	Fe-EDTA (chelate)	5.000
Boron (B)	H_3BO_3	0.500
Manganese (Mn)	$MnCl_2{\cdot}4H_2O$	0.502
Zinc (Zn)	$ZnSO_4{\cdot}7H_2O$	0.050
Copper (Cu)	$CuSO_4{\cdot}5H_2O$	0.020
Molybdenum (Mo)	$Na_2MoO_4{\cdot}2H_2O$	0.011

Values in ppm (mg/L). From Hoagland and Arnon (1950) No. 1 solution, Arnon (1950) revision with Mo = 0.011 ppm, modified with Fe-EDTA according to Jacobson (1951).

essential oil extraction

Extraction was performed by microwave-assisted hydrodistillation (MAHD), following the method of Golmakani and Rezaei (2008) with adaptations. A Samsung MS32J5133AG microwave oven (1.6 kW) connected to a Clevenger-type apparatus with an RW3 water recirculation condenser (Lab Companion) was used. A total of 35 g of dry leaf biomass per experimental unit with 350 mL of distilled water (1:10 w/v) was processed for 45 min at 70 % power. Oil mass was determined with a Highland® HCB 1002 balance. Yield was calculated as:

Yield (%) = oil mass (g) / dry biomass mass (g) × 100

evaluated variables

Vegetative growth: number of stems (≥5 cm with visible node), height (cm) from the collar to the apex, and diameter of the main stem (mm) at 2 cm from the substrate. Measurements were taken twice a week in weeks 1–12 and once a week in weeks 13–16.

Aerial biomass: at 115 dat, total fresh plant weight, fresh leaf weight, and dry leaf weight were recorded. Leaf material was dried at 45 °C to constant weight.

Essential oil yield: determined from 35 g of dry leaf biomass per experimental unit subjected to MAHD.

statistical analysis

Normality assumptions were verified by Shapiro-Wilk and homogeneity of variances by Levene. Height, stem diameter, and oil mass/yield variables met these assumptions and were analyzed by one-way ANOVA and Tukey HSD test (α = 0.05). Number of stems and biomass variables did not meet normality, so they were analyzed by Kruskal-Wallis and Dunn post hoc comparisons with Bonferroni adjustment (α = 0.05). Additionally, height growth kinetics were modeled using the nonlinear logistic model $H(t) = A/[1 + e^{-k(t-tm)}]$, where A is the maximum asymptote (cm), k the relative growth rate, and t_m the inflection point. The maximum absolute growth rate was calculated as $V_{max} = A \times k/4$. The goodness-of-fit metrics (R^2) were obtained with Python 3.12, SciPy, statsmodels, and Matplotlib.

RESULTS

vegetative growth

At the beginning of the experiment (October 5, 2025), all treatments presented homogeneous conditions: average height of 6.00 cm, stem diameter between 5.38 and 5.46 mm, and one stem per plant, ensuring comparability between experimental units.

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At the end of the cycle (week 16), ANOVA detected significant differences between treatments for height ($F_{3,16} = 19.03$; $P < 0.01$) and stem diameter ($F_{3,16} = 33.97$; $P < 0.01$), while Kruskal-Wallis detected differences for number of stems ($H = 12.98$; df = 3; $P < 0.01$). T2 recorded the highest mean height (58.14 ± 4.79 cm), followed by T4 (56.66 ± 4.10 cm), T3 (43.04 ± 4.28 cm), and T1 (41.44 ± 4.82 cm). Post hoc comparisons indicated that T2 and T4 significantly surpassed T1 and T3, with no differences between T2 and T4 or between T1 and T3 (Table 3). As shown in Figure 2, height growth followed a clear upward trend throughout the cycle, with coconut fiber treatments consistently above the others from week 4 onward.

T4 achieved the largest stem diameter (15.24 ± 0.79 mm), with no significant differences from T2 (14.10 ± 0.51 mm), but surpassing T1 (11.26 ± 0.61 mm) and T3 (11.62 ± 0.96 mm); the temporal evolution of this variable is illustrated in Figure 3. For number of stems, T4 (7.8 ± 0.45) significantly surpassed T1 (5.6 ± 0.55), while T2 (7.0 ± 0.71) and T3 (6.2 ± 0.84) showed intermediate values (Table 3). The phenological development recorded throughout the cycle is depicted in Figure 1, and the stem count dynamics are presented in Figure 4.

Table 3. Descriptive statistics and mean comparison for vegetative growth variables at week 16 (n = 5).

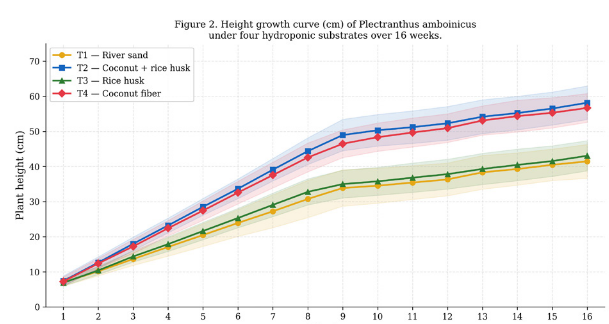
Treat.	Substrate	Height (cm)	Stem diameter (mm)	No. of stems
T1	River sand	41.44 ± 4.82 b	11.26 ± 0.61 b	5.6 ± 0.55 b
T2	Coconut + rice husk	58.14 ± 4.79 a	14.10 ± 0.51 a	7.0 ± 0.71 ab
T3	Rice husk	43.04 ± 4.28 b	11.62 ± 0.96 b	6.2 ± 0.84 ab
T4	Coconut fiber	56.66 ± 4.10 a	15.24 ± 0.79 a	7.8 ± 0.45 a

Means ± standard deviation. For height and diameter, different letters in the same column indicate significant differences according to ANOVA and Tukey HSD ($P < 0.05$); for number of stems, Kruskal-Wallis and Dunn-Bonferroni ($P < 0.05$).

Figure 1. Phenological development of Plectranthus amboinicus grown in a hydroponic system under four sustainable substrates.

Top row: early stage (25 dat); middle row: vegetative growth (45 dat), F corresponds to an individual plant T4 (coconut fiber); bottom row: harvest maturity (105 dat). The arrows ← T1 T2 T3 T4 → indicate the position of each substrate from left to right.

Figure 2. Height growth curve (cm) of *Plectranthus amboinicus* under four hydroponic substrates over 16 weeks.



Shaded bands represent ± 1 standard deviation.

Figure 3. Main stem diameter growth curve (mm) of *Plectranthus amboinicus* under four hydroponic substrates over 16 weeks.

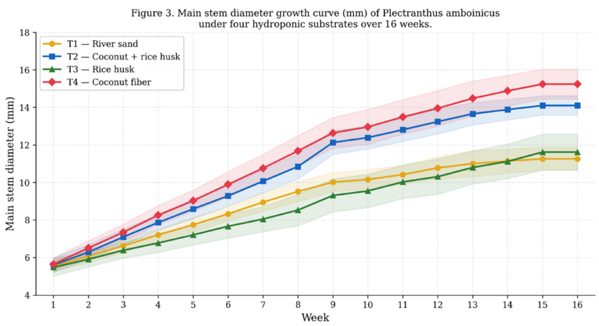
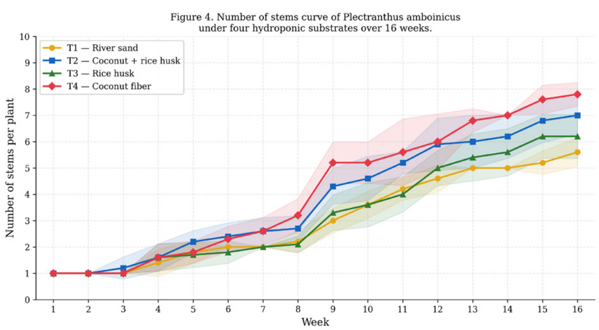


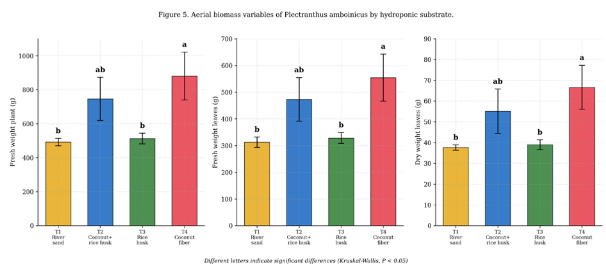
Figure 4. Number of stems curve of *Plectranthus amboinicus* under four hydroponic substrates over 16 weeks.



material biomass

At 115 dat, significant differences were recorded between treatments for total fresh plant weight ($H = 15.00$; $df = 3$; $P < 0.01$), fresh leaf weight ($H = 15.11$; $df = 3$; $P < 0.01$), and dry leaf weight ($H = 14.46$; $df = 3$; $P < 0.01$). T4 presented the highest values in total fresh weight (880.00 ± 140.68 g), fresh leaf weight (554.22 ± 87.98 g), and dry leaf weight (66.62 ± 10.56 g), significantly surpassing T1 and T3. T2 ranked second (745.00 ± 127.06 g; 472.90 ± 81.50 g; 55.10 ± 10.68 g) with no significant differences from T4 or T1. T1 and T3 showed no differences between them. The complete biomass comparisons among treatments are summarized in Table 4 and illustrated in Figure 5.

Figure 5. Aerial biomass variables of Plectranthus amboinicus by hydroponic substrate.



Error bars = ± standard deviation.

essential oil yield

ANOVA revealed significant differences between treatments for essential oil mass ($F_{3,16} = 158.49$; $P < 0.01$). All treatments were statistically different from each other according to Tukey HSD ($\alpha = 0.05$). T4 recorded the highest yield (0.262 ± 0.008 g; 0.748 %), followed by T2 (0.202 ± 0.018 g; 0.577 %), T3 (0.152 ± 0.008 g; 0.434 %), and T1 (0.112 ± 0.008 g; 0.320 %), as detailed in Table 5 and Figure 6. When extrapolating the yield to dry leaf weight per plant, T4 reached an estimated production of 0.499 g of oil/plant, followed by T2 (0.318 g), T3 (0.169 g), and T1 (0.120 g).

Table 4. Descriptive statistics and mean comparison for aerial biomass variables at the end of the cycle (n = 5).

Treat.	Substrate	FW plant (g)	FW leaves (g)	DW leaves (g)
T1	River sand	491.60 ± 21.69 b	312.70 ± 19.61 b	37.62 ± 1.28 b
T2	Coconut + rice husk	745.00 ± 127.06 ab	472.90 ± 81.50 ab	55.10 ± 10.68 ab
T3	Rice husk	512.20 ± 31.67 b	328.12 ± 20.34 b	38.94 ± 2.38 b
T4	Coconut fiber	880.00 ± 140.68 a	554.22 ± 87.98 a	66.62 ± 10.56 a

Means ± standard deviation. Different letters in the same column indicate significant differences (Kruskal-Wallis and Dunn-Bonferroni, P < 0.05). FW = fresh weight; DW = dry weight.

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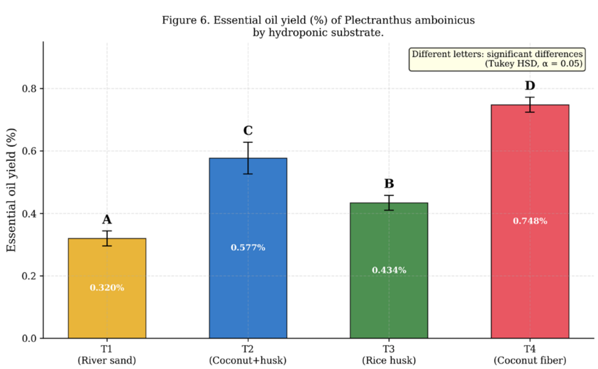
Table 5. Essential oil yield of Plectranthus amboinicus by treatment (n = 5).

Treat.	Substrate	Oil mass (g)	Yield (%)	SD (%)	Group
T1	River sand	0.112 ± 0.008	0.320	0.024	A
T2	Coconut + rice husk	0.202 ± 0.018	0.577	0.051	C
T3	Rice husk	0.152 ± 0.008	0.434	0.024	B
T4	Coconut fiber	0.262 ± 0.008	0.748	0.024	D

Different letters indicate significant differences (Tukey HSD, α = 0.05). Yield calculated on 35 g of dry leaf biomass.

Figure 6. Essential oil yield (%) of *Plectranthus amboinicus* by hydroponic substrate.

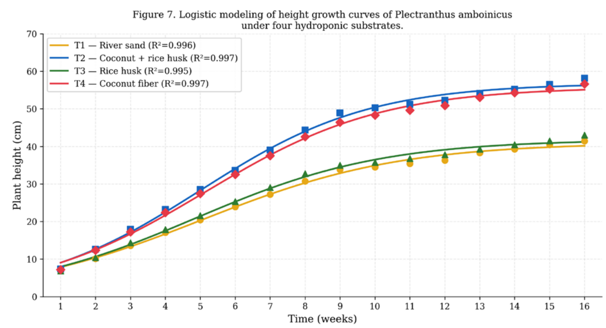


Error bars = ± standard deviation. Different letters indicate significant differences (Tukey HSD, α = 0.05).

growth kinetics

Logistic modeling of weekly height averages demonstrated a high fit for all treatments ($R^2 > 0.99$) (Figure 7). Substrates with coconut fiber (T2 and T4) reached the highest height asymptotes (A = 56.82 and 55.83 cm, respectively) and exhibited the highest maximum growth rates (V_{max}). T2 and T4 recorded V_{max} of 5.88 and 5.53 cm/week, respectively, surpassing T1 (3.63 cm/week) and T3 (3.91 cm/week). The inflection point (t_m) occurred around week 5 in all treatments (Table 6).

Figure 7. Logistic modeling of height growth curves of *Plectranthus amboinicus* under four hydroponic substrates.



Points represent observed averages and lines represent the logistic model fit (R2 > 0.99).

DISCUSSION

The results demonstrated that the type of hydroponic substrate exerts a significant effect on the growth kinetics, biomass, and essential oil yield of *P. amboinicus* under tropical conditions. Substrates with coconut fiber (T2 and T4) consistently surpassed those with lower water retention (T1 and T3) in the evaluated variables.

vegetative growth and biomass

The greater height in T2 (58.14 cm) and T4 (56.66 cm), compared to T1 (41.44 cm) and T3 (43.04 cm), is consistent with Gruda (2019), who notes that

Table 6. Parameters of the logistic growth model for height of *Plectranthus amboinicus* under four hydroponic substrates.

Treat.	Substrate	A (cm)	k (week⁻¹)	tm (week)	Vmax (cm/week)	R^2
T1	River sand	40.99	0.354	5.06	3.63	0.996
T2	Coconut + rice husk	56.82	0.414	5.02	5.88	0.997
T3	Rice husk	41.83	0.374	4.87	3.91	0.995
T4	Coconut fiber	55.83	0.396	5.15	5.53	0.997

A = maximum asymptote; k = relative growth rate; t_m = inflection point; V_{max} = maximum absolute growth rate; R^2 = coefficient of determination of the fit to weekly averages.

substrates with high water retention and adequate root aeration favor vegetative development in soilless systems. The properties of coconut fiber – high porosity, water retention, and near-neutral pH – may explain the better performance of T2 and T4 (Raviv and Lieth, 2008; Abad et al., 2001).

The absence of significant differences in height between T2 and T4 suggests that the presence of coconut fiber, whether pure or in a mixture, was the factor associated with greater growth. T4 showed the largest stem diameter (15.24 mm), without differing from T2, which could be related to a favorable combination of aeration and moisture retention in the root zone (Abad et al., 2001). The similarity between T1 and T3 confirms that both substrates showed limited performance compared to the coconut fiber treatments (Raviv and Lieth, 2008; Barrett et al., 2016). Total fresh biomass values in T4 (880.00 g/plant) exceeded those reported by Sabra et al. (2018) for the species under irrigation every 4 days.

essential oil yield

The maximum yield in T4 was 0.748 % on a dry basis. When standardizing to fresh biomass, using the dry leaf matter proportion observed in T4 (66.62/554.22), the yield was 0.090 %, lower than the 0.2 % on a fresh basis reported by Antonio-Gutiérrez et al. (2023) for *P. amboinicus* grown conventionally in soil. This difference could be related to a possible tissue dilution effect associated with high water availability in hydroponics; however, this interpretation should be considered a hypothesis, because physiological stress indicators and essential oil chemical composition were not directly measured (Adasan et al., 2021).

From a productive perspective, T4 combined higher dry leaf biomass and higher dry-basis yield, reaching an estimated production of 0.499 g of oil/plant, followed by T2 (0.318 g/plant). Altogether, under the evaluated conditions, coconut fiber favored the accumulation of biomass and essential oil yield of *P. amboinicus,* making it a promising substrate for tropical hydroponic systems. A limitation of the study is that only one crop cycle was evaluated, with n = 5 per treatment and without chemical analysis of the essential oil or economic assessment of the system.

CONCLUSIONS

Growth kinetics and vegetative development: The type of hydroponic substrate significantly influences the growth dynamics of *P. amboinicus*. Mathematical modeling confirmed that substrates containing coconut fiber (T2 and T4) drastically accelerated the absolute stem elongation rate ($Vmax$ > 5.5 cm/week) compared to low water-retention media.

Biomass accumulation: Plants grown in pure coconut fiber (T4) showed the highest agronomic vigor, reaching the greatest values for fresh biomass (880.36 g per plant), stem diameter (15.24 mm), and branching. The 1:1 coconut fiber and rice husk mixture (T2) proved statistically comparable in final height and number of stems, validating it as a highly efficient technical alternative.

Essential oil metabolism: The hydric comfort provided by coconut fiber-based hydroponic substrates reduced the percentage concentration of essential oil on a fresh basis (0.09%) by suppressing abiotic stress signals. However, this percentage dilution is largely offset by the absolute volume of extractable biomass produced, resulting in a greater total oil yield per productive unit.

Agroindustrial recommendation: Pure coconut fiber (T4) is ratified as the optimal medium to maximize net essential oil production in large-scale tropical projects. The mixture with rice husk (T2) represents the most viable cost-benefit strategy, promoting regional circular economy by integrating an abundant agroindustrial by-product.

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