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MORALITY BEFORE KNOWLEDGE

Substrate porosity and morphological performance identify an effective growing medium for habanero pepper (*Capsicum chinense* Jacq. cv. Francisca) seedlings

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ABSTRACT

Background: Habanero Francisca pepper (*Capsicum chinense* Jacq.) is an ornamental chili cultivar whose seedling quality is strongly influenced by the composition of the growing medium. Rice husk charcoal, cocopeat, and bamboo compost are commonly used nursery substrates because they improve water retention, aeration, and nutrient availability; however, information regarding their combined use for Habanero Francisca pepper seedlings remains limited. This study aimed to identify an effective growing medium composition based on substrate physical properties and seedling morphological responses. **Methods**: A randomized complete block design with one factor (growing medium composition) and four treatments was applied: M0 (commercial growing medium, control), M1 (rice husk charcoal: cocopeat: bamboo compost = 2:1:1), M2 (1:2:1), and M3 (1:1:2). Substrate properties, including bulk density, particle density, and porosity, were measured. Seedling growth was evaluated through plant height, leaf number, root length, root number, total fresh weight, and total dry weight. Data were analyzed using the F-test followed by Duncan's Multiple Range Test at the 5% significance level. **Findings**: The composition of the growing medium significantly affected plant height, root length, root number, total fresh weight, and total dry weight, but had no significant effect on leaf number. The M2 treatment produced the highest porosity (82.11%) and superior seedling performance, with plant height of 9.55 cm, root length of 10.36 cm, total fresh weight of 0.55 g, and total dry weight of 0.07 g, compared with 5.69 cm, 4.05 cm, 0.25 g, and 0.01 g, respectively, in the control treatment. Higher porosity in M2 likely enhanced root development and resource uptake, resulting in greater biomass accumulation. **Conclusion**: A cocopeat-dominant medium (1:2:1) is the most effective composition for producing high-quality Habanero Francisca pepper seedlings, supporting the use of agricultural residues as a renewable, resource-efficient alternative to commercial peat-based media in pepper nurseries. **Novelty/Originality of this article**: This study is the first to integrate substrate porosity assessment with morphological performance evaluation to determine an effective nursery medium specifically for Habanero Francisca pepper, a cultivar for which such information has not previously been reported.

KEYWORDS: habanero pepper; nursery substrate; porosity; seedling quality.

1. Introduction

Chili pepper (*Capsicum* spp.) is one of the most important horticultural crops cultivated in tropical and subtropical regions for food, industrial, medicinal, and ornamental purposes.

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In Indonesia, peppers represent a valuable commodity due to their high economic value, broad adaptability, and increasing market demand. Successful pepper production largely depends on the quality of seedlings produced during the nursery stage, as vigorous seedlings generally exhibit better establishment, growth, stress tolerance, and productivity after transplanting (Jankauskienė & Laužikė, 2023). Consequently, nursery management practices, particularly the selection of suitable growing media, play a crucial role in determining seedling quality and subsequent field performance. Growing media provide physical support, water, oxygen, and nutrients required for seedling development. The physical characteristics of growing media, including bulk density, particle density, porosity, and water-holding capacity, strongly influence root growth and nutrient uptake.

According to substrate theory, an ideal nursery medium should balance water retention and aeration to ensure adequate oxygen diffusion and moisture availability within the root zone (Caron & Michel, 2021). Excessively high bulk density may restrict root penetration, reduce pore space, and limit oxygen availability, thereby suppressing seedling growth (Ogorek et al., 2025). Conversely, media with excessively low water-holding capacity may lead to rapid moisture loss and reduced nutrient transport. Therefore, optimizing the physical properties of nursery substrates is essential for producing high-quality seedlings. Organic substrate components are widely used in nursery production because they improve both the physical and chemical properties of growing media.

Among these materials, rice-husk charcoal, cocopeat, and compost have received considerable attention. Within the aeration/water-holding capacity trade-off described above, these components occupy complementary positions: rice-husk charcoal favors the high-aeration/low-water-retention end, cocopeat favors the high-water-retention/moderate-aeration end, and bamboo compost contributes mainly nutrients and structural stability rather than shifting the physical balance. Rice-husk charcoal is characterized by high porosity and good drainage capacity, which improve aeration and reduce the incidence of soil-borne pathogens (Choudhary & Machavaram, 2023). Cocopeat has a high water-holding capacity, low bulk density, and a favorable pore distribution, thereby creating suitable conditions for root growth and nutrient absorption (Al-Ajlouni et al., 2024). Compost, particularly bamboo compost, contributes organic matter and essential nutrients, including nitrogen, phosphorus, and potassium (Wu et al., 2022), which are required for vegetative growth and root development. Furthermore, organic compost enhances microbial activity and improves substrate structure, thereby increasing nutrient availability to plants (Goldan et al., 2023). Beyond their agronomic benefits, using these agricultural by-products as nursery substrates represents a resource-efficient, waste-valorizing practice that reduces nursery reliance on non-renewable or imported growing media such as peat.

Numerous studies have reported the beneficial effects of these materials on seedling growth. Rice-husk charcoal has been shown to improve seedling height, root development, and biomass accumulation in several vegetable crops by enhancing substrate aeration and drainage (Júnior et al., 2022). Cocopeat-based substrates have been reported to increase water retention, root biomass, and overall seedling vigor due to their superior moisture-holding properties (Tariq et al., 2026). Likewise, compost application improves substrate fertility and nutrient availability, thereby enhancing vegetative growth and biomass production (Sayara et al., 2020). Previous studies have also demonstrated that combinations of organic substrates often produce better seedling performance than single-component media because they provide a more balanced physical and nutritional environment (Khatri et al., 2025).

Despite these findings, most previous studies have focused on common vegetable crops. In contrast, information regarding the combined use of rice-husk charcoal, cocopeat, and bamboo compost for Habanero Francisca pepper (*Capsicum chinense* Jacq.) seedlings remains limited. In particular, the optimal proportion of these substrate components and their relationship with substrate physical properties have not been clearly established. Moreover, studies integrating substrate porosity assessment with the morphological responses of Habanero Francisca seedlings remain scarce. Habanero Francisca pepper is distinguished by its unique fruit morphology, attractive appearance, and high pungency, making it increasingly popular as both an ornamental and a specialty crop (Muñoz-Ramírez et al., 2020). As demand for ornamental peppers continues to grow, the production of vigorous, uniform seedlings becomes increasingly important.

However, scientific information regarding nursery media optimization for this cultivar remains scarce, thereby limiting the development of efficient nursery practices. Because seedling quality strongly influences transplant survival, early growth, and subsequent crop performance, identifying an effective growing medium is essential (Gallegos-Cedillo et al., 2024). Based on the theory that improved substrate porosity enhances root development, water availability, and nutrient uptake, it was hypothesized that growing media containing a higher proportion of cocopeat would improve substrate physical properties. Consequently, enhance seedling growth and quality, because cocopeat has a lower bulk density and a more favorable pore distribution than rice-husk charcoal or bamboo compost, as described above, a higher proportion of cocopeat in the mixture was expected to increase total porosity and air-filled pore space. Accordingly, three ratios of rice-husk charcoal, cocopeat, and bamboo compost were evaluated (M1 = 2:1:1, M2 = 1:2:1, M3 = 1:1:2) to identify the composition that most effectively enhances seedling growth.

Therefore, this study aimed to evaluate the effects of different combinations of rice-husk charcoal, cocopeat, and bamboo compost on substrate physical properties and seedling morphology, and to identify an effective growing-medium composition for Habanero Francisca pepper. The originality of this study lies in integrating substrate porosity assessment with morphological performance evaluation to determine an effective nursery medium specifically for Habanero Francisca pepper, a cultivar for which such information has not previously been reported.

2. Methods

2.1 Material and experimental design

Planting, maintenance, and morphological observations were conducted in the screenhouse of the Experimental Garden, IPB University, Dramaga, Bogor, Indonesia, from March to May 2024. Substrate porosity analysis was performed at the Laboratory of the Faculty of Animal Science, IPB University. The experimental materials consisted of Habanero 'Francisca' pepper seeds, rice-husk charcoal, cocopeat, bamboo compost, and a commercial ready-to-use growing medium. The experiment was arranged in a one-factor Randomized Complete Block Design (RCBD) with growing medium composition as the treatment factor. Four growing-media formulations were evaluated: M0 (commercial growing medium), M1 (2 rice-husk charcoal: 1 cocopeat: 1 bamboo compost), M2 (1 rice-husk charcoal: 2 cocopeat: 1 bamboo compost), and M3 (1 rice-husk charcoal: 1 cocopeat: 2 bamboo compost) (Table 1). Each treatment was replicated 7 times, yielding 28 experimental units. The block factor represented the spatial positions of seedlings within the tray to minimize the influence of positional variation during seedling growth, and treatments were randomly assigned within each block.

Table 1. Composition ratios of growing media used in pepper seedling raising

No	Treatment	Rice-husk charcoal	Cocopeat	Bamboo compost
1	M0	-	-	-
2	M1	2	1	1
3	M2	1	2	1
4	M3	1	1	2

2.2 Seedling establishment and experimental procedures

Seeds were sown in 128-cell seedling trays under screenhouse conditions. Each treatment occupied 12 cells, with three seeds sown per cell to ensure successful germination. After seedling establishment, seven healthy and uniform seedlings corresponding to the seven predefined block positions were selected for morphological evaluation, with each seedling representing one experimental unit. During the 6-week experimental period, seedlings were irrigated once daily using tap water. Approximately 500 mL of water was uniformly applied to each 128-cell seedling tray to maintain adequate substrate moisture. No supplemental fertilizer or fertigation was applied throughout the experiment. Irrigation and nutrient management were standardized across all treatments to ensure that differences in seedling growth were attributable to differences in growing medium composition rather than variations in water or nutrient supply.

2.3 Porosity measurement

Porosity was determined from the bulk density and particle density of the medium. Bulk density is the soil weight per unit volume, while particle density is the ratio of soil mass to particle volume after oven drying. Equipment and materials used included a ring, calipers, paper, a 100 ml volumetric flask, a pestle and mortar, a funnel, a sieve, an oven, scales, and air-free water. The ring's weight, height, and inner diameter were measured. Bulk density was determined by weighing the medium and dividing by the ring's volume. Samples were oven-dried at 105 °C for 24 hours, and the dry mass was weighed, then calculated using the following formulas:

Porosity of the growing media was determined based on bulk density (BD) and particle density (PD) measurements. Bulk density was defined as the dry mass of the growing medium per unit total volume. In contrast, particle density was defined as the ratio of the dry mass of the medium to the volume occupied by the solid particles. Bulk density was determined using the core method. A cylindrical ring of known dimensions was used, and its weight, height, and internal diameter were measured prior to sampling. The growing medium contained in the ring was oven-dried at 105 °C for 24 h to reach constant weight. The dry mass of the sample was calculated as:

$$SM = (Md + Mr) - Mr \quad \text{(Eq. 1)}$$

SM is the solid mass (g), Md is the mass of the oven-dried sample and ring (g), and Mr is the mass of the empty ring (g). The total volume of the sample (Vt, cm^3) was calculated as:

$$Vt = \pi r^2 t \quad \text{(Eq. 2)}$$

Where r is the internal radius of the ring (cm), and t is the height of the ring (cm). Bulk density (BD, g cm^{-3}) was then calculated using the following equation:

$$BD = \frac{SM}{Vt} \quad \text{(Eq. 3)}$$

Particle density was determined using the volumetric flask method. The growing medium was first ground and sieved to obtain a homogeneous sample. An empty 100-mL volumetric flask (F) was weighed, after which 20 g of the dried sample was added and weighed again (F + S). Air-free water was then added to approximately three-fourths of the flask volume, and the mixture was thoroughly homogenized to remove trapped air. Subsequently, the flask was filled to the 100-mL mark with air-free water and weighed (F + S + W). The solid mass (SM, g) was calculated as:

$$SM = (F + S) - F \quad \text{(Eq. 4)}$$

The solid volume (SV, cm^3) was calculated as:

$$SV = 100 - [(F + S + W) - (F + S)] \quad \text{(Eq. 5)}$$

Particle density (PD, g cm^3) was then calculated as:

$$PD = \frac{SM}{SV} \tag{Eq. 6}$$

Porosity (%) of the growing media was calculated using the following equation:

$$\text{Porosity (\%)} = 1 - (\frac{BD}{PD}) \times 100 \tag{Eq. 7}$$

2.4 Observed parameters and data analysis

Seedling growth was evaluated using several morphological parameters. Plant height (cm) was measured weekly from the surface of the growing medium to the apical growing point, with the tallest leaf positioned upright to ensure measurement consistency. The number of leaves was recorded weekly by counting only fully expanded leaves. At the end of the experimental period, root length (cm) was measured with a ruler, and root number was assessed after carefully washing the root system to remove adhering media and expose the root hairs. Total fresh weight (g) was measured by weighing the entire plant immediately after harvest using a digital balance. Total dry weight (g) was determined by oven-drying individual plants at 50 °C for 72 hours until a constant weight was achieved, then weighing with a digital balance.

All experimental data were analyzed using analysis of variance (ANOVA) with the General Linear Model (GLM) procedure in the Statistical Analysis System (SAS) software (SAS Institute Inc., Cary, NC, USA). Microsoft Excel was used for data organization and preliminary calculations. The analysis was conducted to evaluate the effects of different growing media compositions on the morphological growth responses of Habanero pepper seedlings. Prior to analysis, the data were examined for consistency and suitability for ANOVA assumptions. Treatment means were compared using Duncan's Multiple Range Test (DMRT) at the 5% significance level ($P \leq 0.05$) whenever the F-test detected significant differences among treatments. Results are presented as mean ± standard deviation (SD). In addition to significance levels, the corresponding F-values, degrees of freedom (df), and exact P-values obtained from the ANOVA are reported for each measured parameter to provide a complete statistical description of the treatment effects.

3. Results and Discussion

3.1 Medium condition

Bulk density, particle density, and porosity are important physical properties of growing media because they determine the root-zone environment by influencing aeration, water retention, root penetration, and nutrient availability. Variations in these properties may consequently affect seedling growth and development. The physical characteristics of the growing media used in this study are presented in Table 2, which shows substantial differences in bulk density, particle density, and porosity among the tested media.

Table 2. Bulk density, particle density, and porosity of the growing media

Treatment	Bulk density (g/cm^3)	Particle density (g/cm^3)	Porosity (%)
M0	0.28	1.25	77.20
M1	0.23	0.95	75.79
M2	0.17	0.95	82.11
M3	0.19	0.95	80.00

Notation: M0= ready-to-use media; M1= Husk charcoal [2]: Cocopeat [1]: bamboo compost [1]; M2= husk charcoal [1]: cocopeat [2]: bamboo compost [1]; M3= Husk charcoal [1]: Cocopeat [1]: bamboo compost [2]

The physical characteristics of the growing media varied considerably among treatments (Table 2). The highest bulk density was observed in M0 (0.28 g/cm^3), whereas the lowest value was recorded in M2 (0.17 g/cm^3). Bulk density is an important indicator of substrate compaction because it influences pore space, root penetration, and water movement within the growing medium. The lower bulk density observed in M2 indicates that this medium had a looser and less compact structure, which likely facilitated root proliferation and improved root exploration of the substrate. In contrast, the relatively high bulk density of M0 suggests a denser substrate that may have restricted root penetration and reduced gaseous exchange within the root zone. Particle density values were similar in M1, M2, and M3 (0.95 g/cm^3) but substantially higher in M0 (1.25 g/cm^3). The lower particle density in the amended media may be attributed to the incorporation of organic components, particularly cocopeat and bamboo compost, which are inherently less dense than mineral-based substrates.

Organic materials generally improve substrate structure by increasing pore space and reducing compaction, thereby creating a more favorable environment for root growth (Durand et al., 2024). Media porosity ranged from 75.79% to 82.11%, with M2 exhibiting the highest porosity, followed by M3, M0, and M1. High substrate porosity is essential for maintaining a balance between water retention and air-filled pore space, both of which are critical for root respiration and nutrient uptake. The high porosity observed in M2 indicates that this medium provided greater pore space for water and air storage, thereby enhancing oxygen diffusion and promoting microbial activity in the rhizosphere (Negi et al., 2025). Adequate oxygen availability is particularly important for sustaining root respiration, which supplies the energy required for nutrient absorption and root elongation (Tarkowski et al., 2023).

The favorable combination of low bulk density and high porosity in M2 was consistent with the superior growth responses observed in this study, including greater plant height, root length, and biomass accumulation. These results suggest that a higher proportion of cocopeat in M2 improved the substrate's physical quality by enhancing moisture retention while maintaining adequate aeration. Conversely, the lower porosity and higher bulk density observed in M0 may have reduced oxygen availability in the root zone, thereby limiting seedling growth. Overall, the physical characterization results demonstrate that M2 provided the most suitable root-zone environment among the tested media, which ultimately contributed to the enhanced growth of Habanero 'Francisca' pepper seedlings through improved aeration, water retention, and root system development.

3.2 Pepper seedling growth

Analysis of variance revealed that growing medium composition significantly affected plant height, root length, root number, total fresh weight, and total dry weight. In contrast, leaf number was not significantly influenced by the treatments (Table 3). Table 3 summarizes the endpoint (6 WAP) values for all parameters; the corresponding week-by-week or parameter-specific data are presented in full in Tables 4–7 and discussed in Sections 3.3–3.6. These findings indicate that variations in the physical properties of the growing media primarily affected seedling growth and biomass accumulation rather than leaf production.

Growing medium composition significantly affected most growth parameters of Habanero 'Francisca' pepper seedlings at 6 weeks after planting (WAP), except for leaf number (Table 3). Seedlings grown in M2 exhibited the greatest overall growth performance, as indicated by the highest plant height, root length, root number, fresh weight, and dry weight. In contrast, the commercial medium (M0) generally resulted in the poorest growth. The composition of the growing medium significantly influenced plant height. Seedlings grown in M2 attained the greatest height (9.55 cm), followed by M3 and M1, whereas those grown in M0 were significantly shorter (5.69 cm). The superior shoot growth observed in M2 suggests that the balanced proportion of cocopeat, rice husk charcoal, and bamboo compost provided favorable physical and nutritional conditions for vegetative development. Cocopeat contributes high water-holding capacity, rice husk charcoal improves substrate aeration and porosity, and bamboo compost supplies essential nutrients and organic matter. The synergistic effects of these components likely enhanced nutrient uptake and supported greater shoot elongation (Vázquez-Hernández et al., 2019).

Table 3. Plant height, leaf number, root length, root number, total fresh weight, and total dry weight of Habanero Francisca pepper seedlings under different growing media compositions at 6 weeks after planting (WAP)

Treatment	Parameters					
	PH (cm)	LN (leaf)	RL (cm)	RN (root)	FW (g)	DW (g)
M0	5.69b ± 1.25	7.70a ± 0.75	4.05c ± 1.61	7.55a ± 3.29	0.25b ± 0.10	0.01c ± 0.01
M1 (2:1:1)	8.80a ± 0.62	7.66a ± 1.24	7.91ab ± 3.51	7.3a ± 1.77	0.52a ± 0.16	0.05a ± 0.01
M2 (1:2:1)	9.55a ± 0.76	8.79a ± 1.50	10.36a ± 2.55	7.86a ± 2.41	0.55a ± 0.17	0.07a ± 0.02
M3 (1:1:2)	8.95a ± 1.45	8.10a ± 1.96	5.44bc ± 1.96	4.00b ± 1.67	0.34b ± 0.07	0.03a ± 0.01
F (3.24)	20.76	0.94	8.59	4.03	8.35	26.67
p-value	< 0.0001 **	0.4373 ns	0.0005 **	0.0188 *	0.0006 **	< 0.0001 **

Notes: Data followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level ($P \leq 0.05$). Values are expressed as mean ± standard deviation. **= highly significant; ns = not significant effect. Notation: M0= ready-to-use media; M1= Husk charcoal [2]: Cocopeat [1]: bamboo compost [1]; M2= husk charcoal [1]: cocopeat [2]: bamboo compost [1]; M3= Husk charcoal [1]: Cocopeat [1]: bamboo compost [2]; PH = plant height, LN = leaf number, RL = root length, RN = root number, FW = fresh weight, and DW = dry weight

Leaf number did not differ significantly among treatments, despite numerical differences ranging from 7.66 to 8.79 leaves per plant. This finding indicates that leaf production in Habanero pepper seedlings was relatively stable across the tested growing media. Genetic and developmental factors generally regulate leaf initiation and may therefore be less responsive to moderate variations in substrate composition than other growth traits. Root development responded strongly to the composition of the growing medium. M2 produced the longest roots (10.36 cm) and the highest root number (7.86 roots plant^{-1}), whereas M3 resulted in the lowest root number, and M0 produced the shortest roots. These results indicate that M2 provided a more favorable root-zone environment, characterized by improved aeration, moisture retention, and nutrient availability. Adequate oxygen supply within the substrate is essential for root respiration and cell division, thereby promoting root elongation and lateral root formation (Balliu et al., 2021). Conversely, the lower root growth observed in M0 and M3 suggests that the physical characteristics of these media were less suitable for root development.

Biomass accumulation, as reflected by fresh and dry weight, was also significantly affected by growing medium composition. M2 produced the highest fresh weight (0.55 g) and dry weight (0.07 g), although these values were statistically similar to those obtained in M1. In contrast, M0 exhibited the lowest biomass accumulation. Greater biomass production in M1 and M2 was likely associated with their more extensive root systems, which enhanced water and nutrient acquisition. Improved resource uptake promotes photosynthetic activity and assimilate production, ultimately resulting in greater dry matter accumulation. Overall, the results demonstrate that the M2 treatment (1:2:1) was the most effective growing medium composition for promoting seedling growth, particularly in terms of shoot development, root system architecture, and biomass accumulation. These findings highlight the importance of achieving an appropriate balance among substrate components to optimize the physical and nutritional properties of the growing medium and thereby improve seedling quality (Othman et al., 2019).

3.3 Plant height

Significant differences in plant height were observed from 2 weeks after planting (WAP) until the end of the observation period. At 2 WAP, seedlings grown in M1 and M2 exhibited the greatest plant height. From 3 WAP onward, however, M2 consistently showed superior growth performance compared with the other treatments (Table 4). During the later growth stages (4–6 WAP), seedlings grown in M1, M2, and M3 were significantly taller than those grown in the commercial medium (M0). In contrast, no significant differences were detected among the three mixed-media treatments. The increased plant height observed in media containing rice husk charcoal, cocopeat, and bamboo compost may be attributed to improved nutrient availability and more favorable physical conditions, such as enhanced aeration, water retention, and root development. Previous studies have demonstrated that growing media containing cocopeat and rice husk charcoal can promote vegetative growth by improving moisture retention, nutrient availability, and substrate aeration (Taofik et al., 2019).

Table 4. Plant height of Habanero Francisca pepper seedlings during 6 weeks after planting (WAP)

Treatment	1 WAP (cm)	2 WAP (cm)	3 WAP (cm)	4 WAP (cm)	5 WAP (cm)	6 WAP (cm)
M0	2.05 ± 0.13	2.67 ± 0.24 b	3.00 ± 0.86 b	3.45 ± 1.07 b	4.55 ± 1.40 b	6.76 ± 1.24 b
M1 (2:1:1)	2.55 ± 0.52	3.46 ± 0.70 a	3.80 ± 0.86 b	5.52 ± 1.12 ab	7.28 ± 1.32 a	9.34 ± 0.78 a
M2 (1:2:1)	2.64 ± 0.34	3.76 ± 0.26 ab	4.34 ± 0.83 a	5.34 ± 1.31 a	6.81 ± 0.99 a	8.83 ± 0.70 a
M3 (1:1:2)	2.58 ± 0.53	3.73 ± 0.76 a	3.82 ± 1.14 ab	4.86 ± 1.62 a	6.52 ±1.39 a	8.92 ± 1.41 a
F (3.24)	3.04	6.06	2.47	3.65	6.11	8.10
p-value	0.0484 *	0.0032 **	0.0863 ns	0.0267*	0.0031**	0.0007 **

Notes: Data followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level (P ≤ 0.05). Values are presented as mean ± standard deviation. * = significant; ** = highly significant; ns = not significant. Notation: M0= ready-to-use media; M1= Husk charcoal [2]: Cocopeat [1]: bamboo compost [1]; M2= husk charcoal [1]: cocopeat [2]: bamboo compost [1]; M3= Husk charcoal [1]: Cocopeat [1]: bamboo compost [2]; WAP = Week After Planting

Growing media had no significant effect on plant height during the first week after planting, suggesting that early seedling growth primarily depended on seed reserves. Significant differences emerged from 2 WAP onward, with mixed-media treatments generally outperforming the commercial medium. M2 consistently produced taller seedlings throughout the experimental period, although no significant differences were observed among M1, M2, and M3 during the final growth stages. The superior performance of mixed-media treatments was likely associated with improved substrate porosity, aeration, water retention, and nutrient availability, which collectively enhanced root development and vegetative growth.

According to Irfan et al. (2024), early seedling growth depends largely on the mobilization of seed reserves before seedlings become capable of effective photosynthesis and nutrient uptake from the growing medium. The enhanced plant height observed in the mixed-media treatments was likely associated with improved substrate physical properties, including greater porosity, aeration, and water-holding capacity, which supported root development and more efficient nutrient uptake. Media with adequate aeration and water retention enable roots to absorb water and nutrients more effectively, thereby promoting cell division and elongation, processes directly involved in stem growth (Wei et al., 2024).

In addition, cocopeat possesses a high water-holding capacity, whereas rice husk charcoal improves substrate aeration and drainage; consequently, their combination may create a more favorable root-zone environment for seedling growth (Atzori et al., 2021). Bamboo compost also supplies essential nutrients, particularly nitrogen, phosphorus, and potassium, which are required for vegetative development (Sim et al., 2025). Collectively, these properties enhanced vegetative growth, as reflected by greater increases in plant height in the mixed-media treatments compared with the control.

3.4 Number of leaves

Leaf number is commonly used as an indicator of vegetative growth and the photosynthetic capacity of plants. Analysis of variance showed that the growing medium composition exerted only a minor effect on this parameter during the experimental period, with significant differences detected only at 4 and 5 WAP (Table 5). The limited response of leaf number suggests that leaf initiation in Habanero pepper seedlings was less sensitive to moderate variations in substrate composition.

Table 5. Leaf number of Habanero Francisca pepper seedlings during 6 weeks after planting (WAP)

Treatment	1 WAP	2 WAP	3 WAP	4 WAP	5 WAP	6 WAP
M0	2 ± 0	2 ± 0	3.2 ± 1.02	5.11 ± 1.06 b	5.87 ± 1.13 a	7.72 ± 0.77
M1 (2:1:1)	2 ± 0	2 ± 0	3.4 ± 0.95	6.02 ± 0.2 a	5.83 ± 0.33 a	7.88 ± 1.21
M2 (1:2:1)	2 ± 0	2 ± 0	4 ± 0.1	6.01 ± 0.1 a	6.71 ± 1.21 a	8.77 ± 1.54
M3 (1:1:2)	2 ± 0	2 ± 0	3.2 ± 1.03	5.58 ± 0.1 a	4.52 ± 1.68 b	8.03 ± 0.88
F (3.24)	-	-	1.33	4.41	4.04	1.16
p-value	-	-	0.2874 ^{ns}	0.0132*	0.0186*	0.3455 ^{ns}

Notes: Data followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level (P ≤ 0.05). Values are presented as mean ± standard deviation. * = significant; ** = highly significant; ns = not significant. Notation: M0= ready-to-use media; M1= Husk charcoal [2]: Cocopeat [1]: bamboo compost [1]; M2= husk charcoal [1]: cocopeat [2]: bamboo compost [1]; M3= Husk charcoal [1]: Cocopeat [1]: bamboo compost [2]; WAP = Week After Planting

Growing medium composition had limited effects on leaf production in Habanero 'Francisca' pepper seedlings throughout the experimental period (Table 5). No significant differences in leaf number were observed during the first 3 weeks after planting (WAP), indicating that early leaf development was largely dependent on seed reserves rather than substrate composition (Welch, 2024). Significant differences in leaf number were detected only at 4 and 5 WAP. At 4 WAP, seedlings grown in the mixed-media treatments (M1, M2, and M3) produced significantly more leaves than those grown in the commercial medium (M0), suggesting that the incorporation of organic amendments marginally enhanced vegetative development. At 5 WAP, M2 produced the highest leaf number, whereas M3 resulted in the lowest value.

The superior performance of M2 may be attributed to its balanced composition of cocopeat, rice husk charcoal, and bamboo compost, which likely improved substrate moisture retention, aeration, and nutrient availability. Cocopeat possesses a high water-holding capacity, while rice husk charcoal enhances substrate porosity and aeration, thereby creating favorable conditions for plant growth (Jayaprakash & Balamurugan, 2022; Homchat & Ramphueiphad, 2022). In addition, bamboo compost supplies organic matter and essential nutrients that support leaf development (Nong et al., 2025).

Conversely, the relatively lower leaf number observed in M3 may indicate that the higher proportion of bamboo compost created less favorable substrate conditions for leaf initiation. Despite these transient differences, leaf number did not differ significantly among treatments at 6 WAP, suggesting that all growing media were ultimately capable of sustaining adequate leaf production. Overall, leaf production appeared less responsive to moderate variations in substrate composition than other growth parameters, such as root development and biomass accumulation.

3.5 Root length and number of roots

The composition of the growing media influenced root growth. Seedlings grown in M2 produced the longest roots and the greatest number of roots, indicating superior root system development compared with the other treatments (Table 6). The enhanced root growth observed in M2 is likely related to its higher porosity and lower bulk density, which provided a favorable environment for root penetration, oxygen diffusion, and water retention.

Table 6. Root length and root number of Habanero Francisca pepper seedlings at 6 weeks after planting (WAP)

Treatments	Root length (cm)	Number of root (root)
M0	4.05 ± 1.71 c	7.55 ± 3.29 a
M1 (2:1:1)	7.91 ± 3.55 ab	7.31 ± 1.77 a
M2 (1:2:1)	10.36 ± 2.66 a	7.86 ± 2.41 a
M3 (1:1:2)	5.44 ± 1.96 bc	4.00 ± 1.67 b
F (3.24)	8.59	4.03
p-value	0.0005**	0.0188*

Notes*: Data followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level ($P \leq 0.05$). Values are presented as mean ± standard deviation. ** = highly significant; ns = not significant. Notation: M0= ready-to-use media; M1= Husk charcoal [2]: Cocopeat [1]: bamboo compost [1]; M2= husk charcoal [1]: cocopeat [2]: bamboo compost [1]; M3= Husk charcoal [1]: Cocopeat [1]: bamboo compost [2]; WAP = Week After Planting

Growing media composition had a highly significant effect on root length and root number of Habanero pepper seedlings (Table 6). The M2 treatment (1:2:1) produced the greatest root length, whereas the M0 treatment resulted in the shortest roots. These results indicate that the media composition used in M2 was more effective in supporting root system development than the other treatments. The greater root length observed in M2 was likely associated with a more favorable balance among substrate porosity, aeration, and water-holding capacity. Such conditions enable roots to develop more effectively and explore the growing medium for water and nutrient acquisition. In addition, high porosity enhances oxygen diffusion within the root zone, thereby supporting root respiration and the metabolic activities required for root growth and elongation (Li et al., 2025). According to Shahmansouri et al. (2025), growing media with adequate porosity and aeration promote root growth by providing sufficient oxygen for root respiration.

In contrast, the shorter roots observed in M0 and M3 suggest that the physical properties of these media were less conducive to root development, thereby restricting root penetration and elongation. A similar response was observed for root number. The M2 treatment produced the highest number of roots, whereas M3 produced the fewest. The lower root number in M3 indicates that the proportion of substrate components in this treatment was less capable of providing optimal conditions for new root formation. Lateral root formation is strongly influenced by the availability of oxygen, water, and physical space within the growing medium (Zhang et al., 2023). Media with excessive compaction or inadequate aeration can inhibit the initiation and development of lateral roots (Xu et al., 2025).

According to El Amrani (2023), root system development is strongly influenced by the physical properties of the growing medium because roots require a balance between water availability and oxygen supply to support cell division and elongation. A well-developed root system plays a critical role in enhancing the plant's capacity to absorb water and nutrients, ultimately supporting overall vegetative growth. Greater root length and a higher number of roots increase the absorptive surface area, thereby improving nutrient uptake efficiency and the translocation of assimilates to the shoot. Maqbool et al. (2022) reported that an extensive root system enables plants to utilize water and nutrient resources more efficiently, thereby promoting plant growth and biomass accumulation. These results confirm that the lower bulk density and higher porosity of M2 directly translated into a more extensive root system compared with the other media.

3.6 Fresh and dry weight of plants

The accumulation of fresh and dry weight was significantly affected by the composition of the growing medium. Seedlings grown in M1 and M2 exhibited greater total fresh weight and dry weight than those grown in M0 and M3 (Table 7). The positive relationship between fresh weight and dry weight indicates that treatments that promote water uptake also enhance biomass production and assimilate accumulation.

Table 7. Total fresh weight and total dry weight of Habanero Francisca pepper seedlings at 6 weeks after planting (WAP)

Treatments	Fresh weight of plants (g)	Dry weight of plants (g)
M0	0.25 ±0.10 b	0.01 ± 0.01 c
M1 (2:1:1)	0.52 ± 0.16 a	0.05 ± 0.01 a
M2 (1:2:1)	0.55 ± 0.17 a	0.07 ± 0.02 a
M3 (1:1:2)	0.34 ± 0.07 b	0.03 ± 0.01 a
F (3.24)	8.35	26.67
p-value	0.0006**	< 0.0001**

Notes*: Data followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level (P ≤ 0.05). Values are presented as mean ± standard deviation. ** = highly significant; ns = not significant. Notation: M0= ready-to-use media; M1= Husk charcoal [2]: Cocopeat [1]: bamboo compost [1]; M2= husk charcoal [1]: cocopeat [2]: bamboo compost [1]; M3= Husk charcoal [1]: Cocopeat [1]: bamboo compost [2]; WAP = Week After Planting

The M2 treatment (1:2:1) produced the greatest fresh weight, whereas the M0 and M3 treatments resulted in lower fresh weights. The higher fresh weight observed in M2 indicates that this media composition provided more favorable growing conditions, thereby promoting greater biomass accumulation in Habanero pepper seedlings. The increase in fresh weight was closely associated with the plant's ability to absorb water and nutrients from the growing medium. Media with a balanced combination of porosity, aeration, and water-holding capacity can enhance root system development, thereby improving the efficiency of water and nutrient uptake (Tuxun et al., 2025). These conditions ultimately support tissue formation and increase fresh biomass accumulation. According to Fathi (2022), efficient water and nutrient uptake is essential for cell expansion and biomass production during vegetative growth.

A similar trend was observed for plant dry weight. The M2 treatment produced the highest dry weight, whereas the M0 treatment produced the lowest. Dry weight is considered an indicator of organic matter accumulation derived from photosynthesis and reflects overall plant growth performance. The greater dry weight observed in M2 suggests that this growing medium was more effective in supporting photosynthetic activity and the translocation of assimilates than the other treatments. Xia et al. (2024) reported that adequate nutrient availability and favorable root-zone conditions enhance photosynthetic efficiency and promote biomass accumulation in plants. These biomass results reinforce the root and shoot data presented in the preceding sections, indicating that the improved physical conditions of M2 consistently translated into greater resource capture across all growth stages. It should be noted that the underlying physiological mechanisms discussed above, including nutrient uptake efficiency, photosynthetic activity, and assimilate translocation, were not directly measured in this study; these explanations are inferred from the observed morphological and biomass responses in light of the broader substrate-physiology literature, rather than from direct physiological measurements.

Beyond improving seedling growth, the M2 growing medium also has practical and environmental implications for sustainable pepper nursery production. Rice husk charcoal and bamboo compost are abundant agricultural by-products in many rice- and bamboo-producing regions of Indonesia, making them promising alternatives to commercial growing media. Their use may help recycle agricultural waste and reduce reliance on commercial substrates. However, this study did not include an economic analysis or cost comparison between the formulated substrates and the commercial growing medium. Therefore, future research should evaluate production costs, raw material availability, and economic feasibility to determine the practicality of large-scale adoption.

4. Conclusions

This study demonstrated that the physical properties of the growing medium play an important role in determining the quality of Habanero 'Francisca' pepper seedlings. A growing medium (M2) composed of rice husk charcoal, cocopeat, and bamboo compost at a 1:2:1 ratio provided more favorable physical conditions, particularly increased porosity, thereby promoting root development and overall seedling growth. These findings confirm that a balanced composition of growing medium components is a key factor in improving seedling quality during the nursery stage. These results support the use of agricultural by-products, such as rice-husk charcoal and bamboo compost, as renewable, resource-efficient substitutes for peat-based commercial media, aligning nursery practice with more sustainable production systems. This study is limited by its reliance on a single cultivar (Habanero 'Francisca'), a single growing season and screenhouse location, a modest sample size per treatment, and the absence of substrate chemical and nutrient analyses; these factors should be considered when generalizing the findings. Future research should therefore address the chemical characterization of the tested media, validate seedling performance following field transplantation, and evaluate the cost-effectiveness of the M2 formulation relative to commercial substrates. Overall, this study provides new insights that may support the development of nursery techniques and the production of high-quality, sustainably grown pepper seedlings.

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Author Contribution
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The authors declare no conflict of interest.

Declaration of Generative AI Use
During the preparation of this work, the author(s) used a generative AI tool to assist in paraphrasing certain sections for clarity and Grammarly to assist in improving the grammar and academic tone of the manuscript. After using these tools, the author(s) reviewed and edited the content as needed and took full responsibility for the content of the publication.

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