Biochar-Enriched Oil Palm Compost Enhances Growth Performance of Durian Musang King Seedlings

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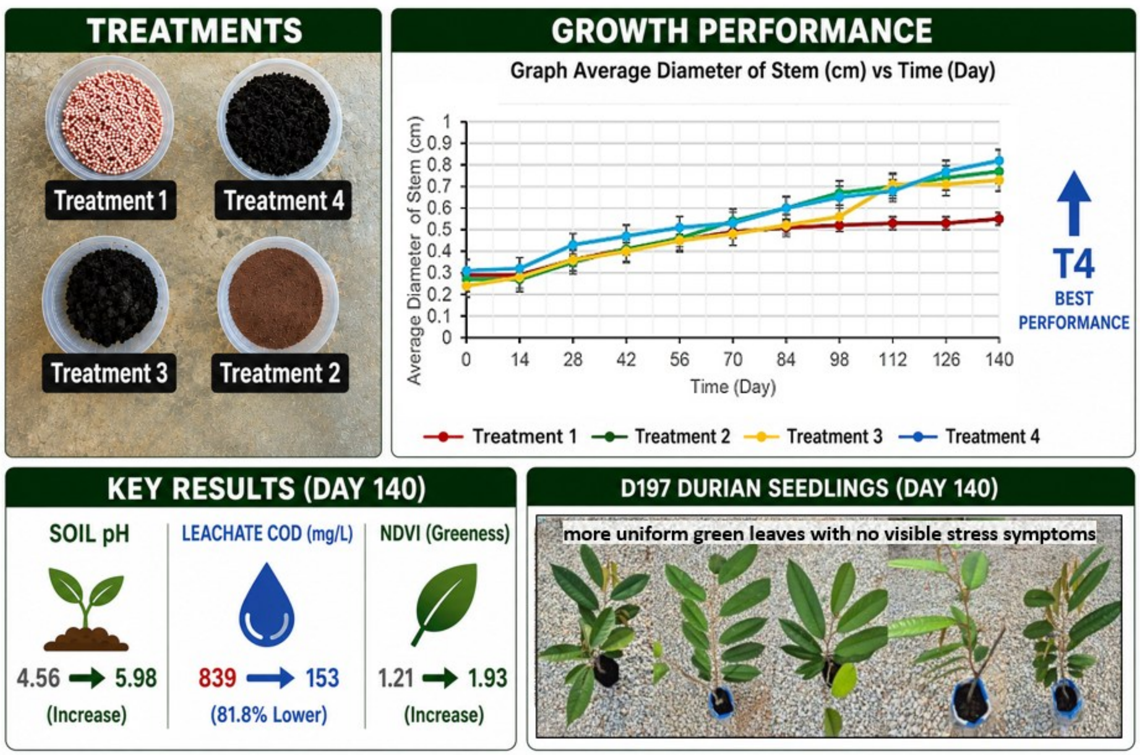
GRAPHICAL ABSTRACT



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Durian 'Musang King' (*Durio zibethinus* D197) cultivation in Malaysia remains heavily reliant on chemical fertilizers, contributing to soil acidification, microbial decline, and nutrient leaching. A 140-day comparative evaluation was conducted of four fertilization regimes: chemical NPK (15:15:15), poultry manure with wood dust, palm oil mill effluent (POME), and biochar-enriched compost. The seedling morphometrics (leaf number, leaf length, stem length, stem diameter, and NDVI) were quantified biweekly, while soil pH, temperature, and leachate COD were monitored to capture nutrient retention dynamics. Biochar-enriched compost (T4) exhibited the most pronounced improvements, surpassing NPK (0.84); soil pH increasing from 4.56 to 5.98 *versus* 4.72–5.62 under NPK; and COD peaking at only 153 mg/L compared with 839 mg/L in manure-based compost (P = 0.010). The biochar-enriched compost improved seedling growth while also reducing nutrient loss, with much lower leaching (153 mg/L compared to 839 mg/L). This means it not only improved plant performance but also protected the environment. By combining plant growth measurements, plant health (NDVI), soil conditions, and leachate analysis, this study provides a practical and well-rounded way to evaluate more sustainable fertilization strategies for durian nursery systems.

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Keywords: Durian seedlings; Musang King; Biochar; Organic fertilizer; Oil palm mill effluent; Nutrient leaching

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INTRODUCTION

Durio zibethinus (Durian) represents one of Southeast Asia's most significant horticultural commodities, with Malaysia ranked the fourth largest global exporter. In 2023, Malaysia exported 27.45 thousand Mt of durian valued at USD 44.49 billion (TradeImeX 2024). Within cultivated varieties, the D197 'Musang King' is the most commercially valuable, driven by its improved organoleptic properties (Khaksar *et al*. 2024). Early-stage fertilization is critical, as suboptimal nutrient management during nursery establishment directly impairs seedling vigor, orchard establishment, and long-term yield.

Conventional durian nurseries predominantly utilize chemical fertilizers for their immediate nutrient availability and economic accessibility (Samsudin *et al*. 2024). Nevertheless, their prolonged use has been associated with soil acidification, nutrient imbalance, microbial suppression, and increased leaching losses (Salamat *et al*. 2024). Organic amendments, derived from manure, composted effluents, and biochar-integrated substrates, have demonstrated potential in enhancing soil physicochemical properties, improving microbial biomass, and sustaining nutrient release (Tugiman *et al*. 2024). The gradual nutrient mineralization of organic formulations aligns more effectively with the nutrient uptake dynamics of perennial tree crops. Evidence from analogous perennial tropical crops such as pineapple, mango, and citrus has demonstrated that organic amendments and biochar can significantly enhance root development, nutrient uptake efficiency, chlorophyll biosynthesis, and soil pH buffering capacity (Fu *et al*. 2025). These improvements have been linked to enhanced microbial activity and more efficient nutrient cycling in the rhizosphere. Despite these advances, comparable studies on durian, particularly high-value cultivars such as D197, remain limited, highlighting a critical knowledge gap in tropical horticultural systems.

Nutrient release varies among organic amendments. Poultry manure supplies ~3% N, 2 to 3% P, and 1 to 2% K (Mondol *et al.* 2025), but its effectiveness depends on microbial activity and environmental conditions. POME-derived compost is richer in organic carbon and micronutrients (Hassan *et al*. 2024), while biochar enhances cation exchange capacity (CEC) and provides porous microhabitats that support microbial colonization (Tugiman *et al*. 2024). Biochar is well known for improving soil physicochemical and biological properties. It can increase CEC by up to ~40% in tropical soils and ~21% in sandy loam, while also enhancing water retention (28.5% increase in available water capacity) (Anyebe *et al.* 2025). Additionally, biochar promotes microbial diversity and activity, contributing to improved nutrient availability. These combined effects enhance nutrient use efficiency and reduce leaching losses, as shown by decreased macronutrient leaching in biochar-amended soils (Chen *et al.* 2025). This broader evidence base suggests that the integration of organic amendments and biochar credibly represents a promising strategy across perennial tropical cropping systems, although its effectiveness in durian nurseries, particularly for elite cultivars such as D197, remains underexplored.

Therefore, this study systematically evaluated four fertilization regimes, NPK (15:15:15), poultry manure with wood dust, POME sludge compost, and biochar-enriched compost, on D197 seedling performance. Over a 140-day cultivation cycle, morphometric parameters (leaf number, leaf length, stem length, stem diameter, and NDVI) were measured biweekly, while soil pH, temperature, and leachate COD were monitored. It is hypothesized that biochar-enriched compost will exhibit improved performance, reflected in enhanced chlorophyll development (NDVI), improved soil chemical stability (pH), and reduced nutrient loss (leachate COD), compared to conventional and other organic fertilization regimes (Hassan and Strezov 2025). Accordingly, this study aimed to quantitatively evaluate the effects of different fertilization regimes using integrated plant, soil, and leachate indicators to test the proposed hypothesis. The inclusion of environmental indicators, particularly leachate COD, offers additional insight into nutrient retention efficiency and environmental impact, positioning this work within the broader framework of sustainable nutrient management and resource conservation.

EXPERIMENTAL

Study Location and Experimental Design

The study was conducted at Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia (UPM), located at 2.987685° N, 101.721760° E. Randomized Complete Block Design (RCBD) was employed, with D197 Musang King Durian seedlings planted 30 cm apart in 7 columns and 3 rows to minimize competition for nutrients, water, and sunlight (Salamat *et al*. 2024). Four fertilization treatments (T1-T4) were applied to five seedlings each (D1-D5), with a control seedling included for comparison. Treatments were replicated across blocks to account for spatial variability (Fig. 1A).

A)

CONTROL	T1D2	T3D4	T1D1	T2D5	T4D3	T1D5
T3D1	T4D2	T1D3	T4D1	T1D4	T3D2	T3D5
T2D2	T3D3	T4D5	T2D3	T4D4	T2D1	T2D4

B)

Fig. 1. (A) The schematic diagram of Randomized Complete Block Design (RCBD) for the arrangement of all D197 Musang King Durian seedlings (T: Treatment; D: Seedling). (B) Fertilizers used for each treatment.

Planting Materials and Fertilizer Treatments

Nursery-propagated clonal D197 (Musang King) seedlings was obtained from Pusat Pertanian Putra, Universiti Putra Malysia. The seedlings, 25 to 30 cm height, 4 to 5 mature leaves in 30×45 cm polybags filled with topsoil (pH 5.7 ± 0.2, organic matter 2.4%) underwent a 7-day acclimatization period before transplantation at the experimental site at INTROP. The study compared conventional chemical fertilizers with organic formulations, as detailed in Table 1. Seedlings were irrigated twice daily (10 min per session) using an automated sprinkler system. Manual weeding was carried out fortnightly, and bio-based insecticide (Milagro Matado, 1% Neem and *Piper sarmentosum*) was applied weekly. Fertilizers were applied at 30-day intervals, with organic fertilizers applied at a higher dosage to compensate for slower nutrient release. Digital images of the fertilizers used in this study are shown in Fig. 1B.

Growth Monitoring, Soil Assessments, Fertilizer Characterization, and Data Analysis

Seedling growth performance was monitored biweekly over a 140-day period. The following parameters were recorded: number of leaves per seedling, average leaf length (cm), stem length (cm), and stem diameter (mm). Leaf number was counted manually, while leaf length was measured from the base to the tip of the longest fully expanded leaf using a 30 cm ruler. Stem length was recorded from the collar to the apical bud, and stem girth was measured at 1 cm above the soil surface using a digital Vernier caliper with 0.01 mm accuracy.

Chlorophyll content was estimated using a Green Seeker Normalized Difference Vegetation Index (NDVI) sensor. The NDVI readings ranged from 0.2 (chlorotic leaves) to 0.8 (healthy green foliage), providing a rapid, non-destructive indicator of plant health and photosynthetic activity. Soil pH and temperature were measured biweekly at a consistent depth of 5 cm using a 4-in-1 soil survey analyzer (model XYZ).

Nutrient Leaching Determination

Leachate samples were collected after each irrigation event using dedicated collection trays (30 cm × 30 cm) placed beneath each polybag. Collected leachate was analyzed for COD using a Hach DR2800 spectrophotometer based on standard method 5220D.

Fertilizers used in each treatment were pre-characterized for key parameters including pH (Hanna HI 98107 digital pH meter). Macronutrient contents were determined using standard analytical methods. Phosphorus (as P_2O_5) and potassium (as K_2O) were measured using inductively coupled plasma optical emission spectrometry (ICP-OES, PerkinElmer Optima 8000), while total nitrogen (N) was determined using the Kjeldahl digestion method. Application levels were standardized to 6 g/seedling/month for the commercial compound fertilizer and 48 g/seedling/month for organic fertilizers, as detailed in Table 1. All quantitative data were statistically analyzed using analysis of variance (ANOVA) in JASP software (version 0.16). Where significant differences were detected ($P < 0.05$), Tukey's Honest Significant Difference (HSD) test was applied for post-hoc pairwise comparisons to determine treatment effects. This approach aligns with practical fertilization strategies employed in nursery systems, where application rates are typically adjusted based on fertilizer type rather than strict mass equivalence.

Table 1. Four Distinct Fertilization Regimes and their Characterizations

Treatment	Fertilizer type	N (%)	P_2O_5 (%)	K_2O (%)	Total Nutrient Content (g/100 g fertilizer)	Application Dosage (g/seedling/month)
1	Commercial NPK compound fertilizer (15:15:15)	15.0	15.0	15.0	45.0	6
2	Organic fertilizer from poultry manure + wood dust	2.5	1.3	2.0	5.8	48
3	Organic fertilizer from treated POME	1.8	1.0	1.5	4.3	48
4	Organic fertilizer enriched with 5% (w/w) biochar	2.0	1.5	2.3	5.8	48

RESULTS AND DISCUSSION

Seedling Growth Performance

Seedlings treated with chemical fertilizer (T1) exhibited the slowest growth across all parameters, with leaf number increasing from 5 to 12 and stem length reaching 21.3 cm (see Fig. 2). This limited growth performance may be attributed to the rapid nutrient release and lack of sustained nutrient availability, which can result in nutrient leaching and reduced long-term uptake efficiency. These findings are consistent with previous studies reporting that chemical fertilizers, while providing immediate nutrient availability, often fail to improve soil organic matter and microbial activity, leading to suboptimal plant development over time (Asadu *et al.* 2024; Pandian *et al.* 2024). In contrast, organic amendments have been shown to enhance nutrient retention and support sustained plant growth.

Leaf production increased from 5 to 12 leaves over the observation period, while average leaf length extended from 9.9 cm to 14.4 cm. Stem length reached 21.3 cm, with stem diameter increasing from 0.29 cm to 0.55 cm. These results corroborate earlier findings on the effectiveness of organic amendments in supporting seedling development. For instance, Bachmann *et al*. (2018) demonstrated that incorporating up to 5% biochar as a peat moss substitute in nursery cultivation maintained healthy growth parameters such as height and collar diameter, without adverse effects. Additionally, the integration of compost and biochar has been shown to enhance soil microbiota diversity, contributing to plant health and improved disease resistance (Bonanomi *et al*. 2020). The deferred need for chemical fertilization in the early stages, observed in this study, is consistent with prior reports suggesting that organic amendments can support initial growth while reducing fertilizer input costs during the first three months (Bachmann *et al*. 2018). Furthermore, the importance of tailored nutrient supplementation is supported by Rohman *et al*. (2013), who reported that optimum growth in durian cultivars such as Durian Jingga and Durian Arab was achieved with NPK applications of 135 g and 180 g per plant, respectively.

In this study, seedlings treated with chemical fertilizer (T1) exhibited the slowest growth across all parameters, with leaf number increasing from 5 to 12 and stem length reaching 21.3 cm. This limited growth performance may be attributed to the rapid nutrient release and lack of sustained nutrient availability, which can result in nutrient leaching and reduced long-term uptake efficiency. These findings are consistent with previous studies reporting that chemical fertilizers, while providing immediate nutrient availability, often fail to improve soil organic matter and microbial activity, leading to suboptimal plant development over time (Asadu *et al.* 2024; Pandian *et al.* 2024). In contrast, organic amendments have been shown to enhance nutrient retention and support sustained plant growth.

The greenness level of the seedlings, as indicated by NDVI, increased progressively across all treatments throughout the study, reflecting overall improvement in vegetative vigor. Treatment 1 (T1) showed an increase from 0.46 to 0.84, indicating moderate to high canopy development. In comparison, organic treatments (T2–T4) exhibited slightly higher final NDVI values, ranging from 0.86 to 0.90. However, these differences were not statistically significant ($P = 0.386$), indicating that all fertilization regimes supported comparable levels of chlorophyll development within the study period. NDVI values between 0.4 and 0.6 are typically associated with developing vegetation, while values above 0.8 indicate dense and healthy canopies with high photosynthetic activity (EOS Data Analytics 2023; Farmonaut 2024), consistent with observations in this study and previous reports (Mulla 2013). The observed numerical trend toward higher NDVI in organic treatments may be associated with improved nutrient availability and soil conditions, including enhanced microbial activity and nutrient retention (Asadu *et al*. 2024). Chemical fertilizers typically lead to rapid nutrient leaching and lack the sustained benefits associated with organic carbon inputs (Pandian *et al*. 2024). The relatively low NDVI indicates suboptimal chlorophyll production, consistent with nitrogen deficiencies emerging late in the growth cycle due to leaching losses (Kizilgeci *et al*. 2021). Nevertheless, NDVI should be interpreted as a supporting physiological indicator, and no definitive differences among treatments can be established based on this parameter alone.

In sharp contrast, seedlings under Treatment 2, receiving laying hens' manure and wood dust, exhibited markedly improved growth across all parameters (Fig. 2). The number of leaves increased rapidly to approximately 25 leaves, with leaf length reaching 16.0 cm. Stem elongation accelerated after Day 42, ultimately reaching 38.9 cm, while stem diameter increased steadily to 0.77 cm. Greenness levels (NDVI) followed a consistent upward trajectory, ending at 0.86. The improved performance of this treatment can be attributed to manure's dual role, providing a rich supply of macro- and micronutrients while simultaneously enhancing microbial activity and soil structure (Liu *et al*. 2024). Manure supplies organic nitrogen and carbon, which stimulate beneficial microbial consortia, improving nutrient cycling and promoting rhizosphere health (Gautam *et al*. 2020). Sawdust further contributes to soil aeration and moisture retention, supporting root development, and enhancing nutrient uptake efficiency (Olatunji *et al*. 2015). These mechanisms explain the enhanced chlorophyll synthesis reflected in higher NDVI, consistent with recent work demonstrating the positive impacts of organic amendments on chlorophyll content in tropical seedlings.

Seedlings receiving POME-derived compost (Treatment 3) showed intermediate but promising growth, particularly for stem elongation. Leaf production reached around 20 leaves, and leaf length increased to 20.1 cm. Stem length, however, reached the highest value across all treatments at 43.7 cm, with stem diameter reaching 0.73 cm. NDVI increased consistently, peaking at 0.89 (Fig. 2). The observed pattern reflects organic fertilizer from POME response as a slow-release organic amendment, enriched with carbon, nitrogen, and trace elements (Salamat *et al*. 2019). As microbial communities decompose organic residues, they gradually release nutrients, supporting sustained stem elongation (Wang *et al*. 2025). However, incomplete decomposition or microbial nutrient immobilization likely contributed to the leaf number plateau after Day 84, which is a known issue in high-carbon organic waste amendments (Khairuddin *et al*. 2016). The high final NDVI highlights enhanced chlorophyll synthesis, consistent with improved nitrogen supply under organic amendments.

It is important to note that organic fertilizers were applied at higher rates (48 g seedling^{-1} month^{-1}) compared to chemical fertilizer (6 g seedling^{-1} month^{-1}) (Table 1), reflecting their lower nutrient density and slower nutrient release characteristics. Unlike synthetic fertilizers, organic amendments rely on microbial mineralization to gradually release nutrients, necessitating higher application rates under practical nursery conditions. Consequently, the observed improvements in plant growth and soil properties under organic treatments may arise not only from nutrient supply but also from enhanced soil structure, moisture retention, and microbial activity. These effects represent inherent functional advantages of organic amendments rather than experimental bias.

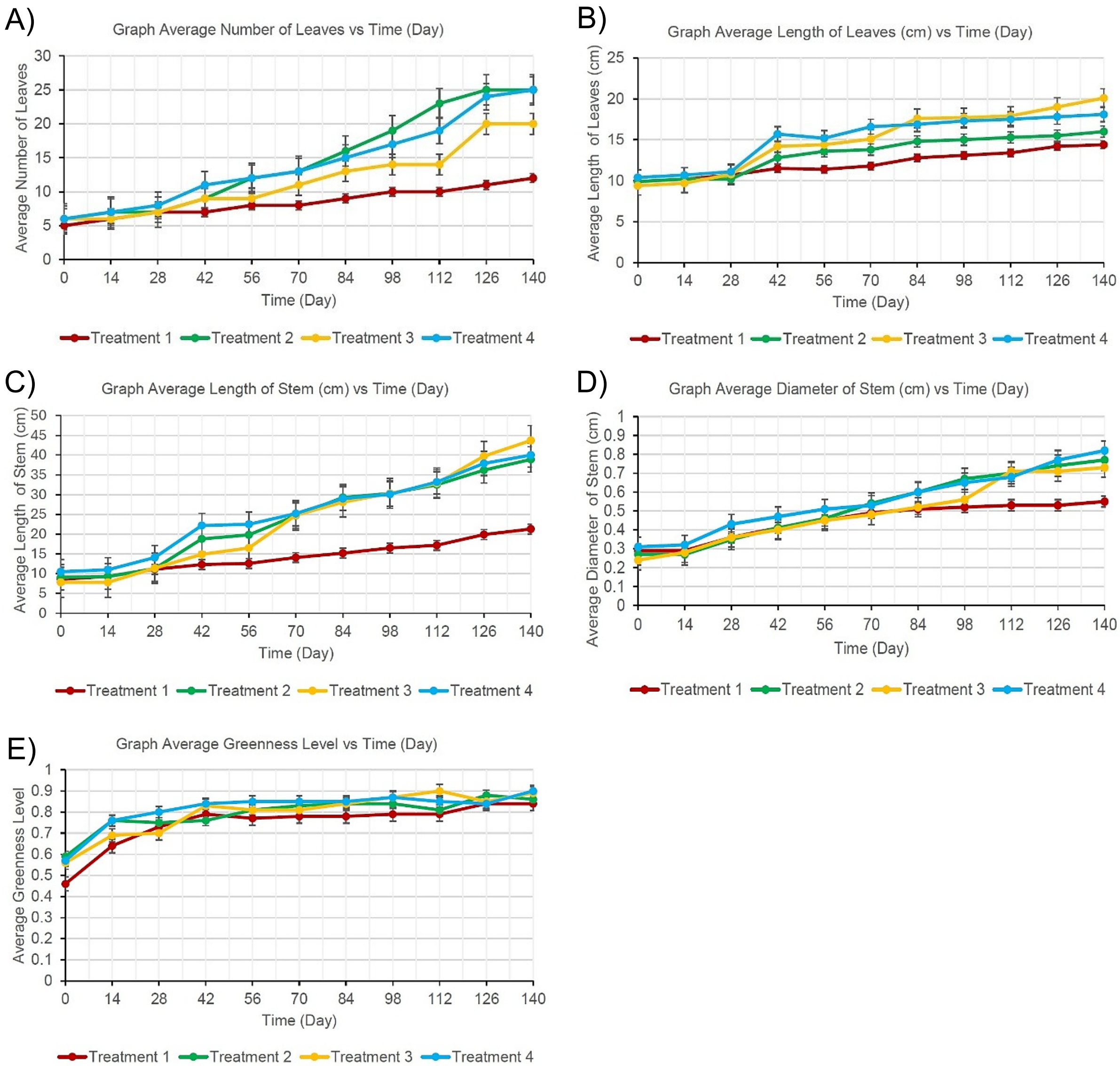

Fig. 2. Growth performance of durian seedlings over 140 days under four fertilizer treatments: (A) Number of leaves, (B) leaf length, (C) stem length, (D) stem diameter, and (E) greenness level

Treatment 4, incorporating biochar into the organic compost, delivered the most consistent and overall improved performance across nearly all parameters (see Fig. 2). Leaf production reached 25 leaves by Day 140, leaf length extended to 21.8 cm, stem length reached 40.0 cm, and stem diameter increased to 0.82 cm, the highest among all treatments. NDVI followed a steady upward trend, ending at 0.90, the highest greenness recorded. Biochar's well-documented ability to enhance soil aeration, moisture retention, and nutrient retention explains these benefits (Zakaria *et al*. 2023). Biochar also serves as a stable habitat for beneficial microbes, fostering microbial colonization and nutrient mineralization. These mechanisms support strong root development, which in turn drives both leaf and stem growths. Biochar's ability to buffer nutrient fluctuations reduces nutrient stress during critical growth stages, further contributing to the observed consistent performance (Kalu *et al*. 2021). The high final NDVI confirms enhanced chlorophyll synthesis, reflecting efficient nitrogen cycling and water management within the biochar-amended root zone. Recent meta-analyses further corroborate that biochar-enhanced soils routinely outperform conventional and organic-only systems in promoting seedling vigor and photosynthetic performance (Zhang *et al*. 2024).

Soil pH and Temperature

Figure 3 illustrates the influence of fertilizer type on soil properties and leachate characteristics, specifically soil pH, temperature, and COD, which indirectly affect seedling growth performance. The results clearly demonstrate that fertilizer type strongly influences soil properties and the growth performance of durian seedlings, particularly through its effects on soil pH and temperature. Treatment 1, which involved the application of synthetic NPK fertilizer, provided only modest improvement in soil pH, rising from 4.72 to 5.62 by Day 140.

This limited pH adjustment reflects the well-documented lack of buffering capacity associated with chemical fertilizers, which contribute minimal organic carbon to support microbial activity and long-term pH stability (Wang *et al*. 2023). Soil temperature under Treatment 1 remained relatively stable (30.0 to 32.0 °C), consistent with the absence of organic decomposition (Citak and Sonmez 2010). Consequently, seedlings in Treatment 1 exhibited poorer growth, producing only 12 leaves with a final leaf length of 14.4 cm and stem length of 21.3 cm. The low NDVI (0.84) reflects suboptimal chlorophyll content, consistent with inefficient nutrient uptake due to the lack of microbial enhancement in the rhizosphere (Are *et al*. 2021).

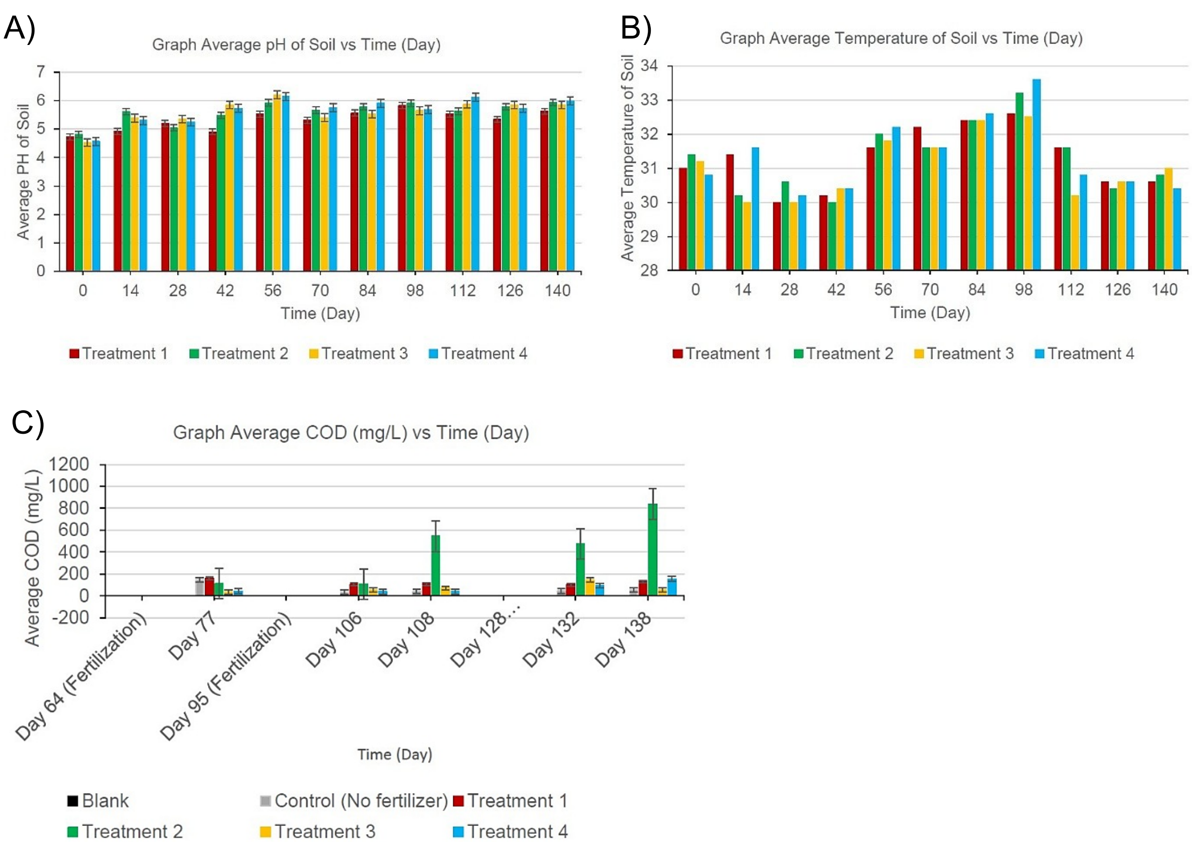

Fig. 3. Temporal changes in (A) soil pH, (B) soil temperature, and (C) COD values over 140 days across four fertilizer treatments.

In contrast, Treatment 2, which combined laying hens' manure with wood dust, significantly improved soil pH from 4.80 to 5.94. This pH improvement reflects the alkaline by-products released during microbial decomposition of manure, which enhances buffering capacity (Yuan and Xu 2011). Although organic amendments such as manure may contribute to heat generation through microbial activity (Kelley 2022), the observed temperature differences among treatments were small (from 31.4 °C to 32.6 °C) and did not indicate a consistently greater warming effect in any single treatment. Nevertheless, this enriched soil environment supported strong seedling growth, with 25 leaves, leaf length of 16.0 cm, and stem length of 38.9 cm. NDVI also increased to 0.86, confirming improved chlorophyll synthesis under enhanced nutrient cycling (Mthiyane *et al*. 2024).

Treatment 3, incorporating compost derived from palm oil mill effluent (POME), provided gradual but effective pH recovery, increasing from 4.52 to 5.84 by Day 140. This gradual adjustment reflects the slow mineralization and nutrient release characteristic of POME-based organic matter (Kim *et al*. 2015). Soil temperature (30 °C to 32.5 °C) indicated moderate microbial activity, aligned with the progressive breakdown of POME residues. This steady nutrient supply supported the tallest seedlings among all treatments, with stem length reaching 43.7 cm. However, leaf count (20) and leaf length (20.1 cm) were slightly lower than those in Treatments 2 and 4, likely due to slower nitrogen release and microbial immobilization early in the nursery period. NDVI reached 0.89, indicating sustained chlorophyll synthesis under stable nutrient conditions.

Treatment 4, which combined compost with biochar, provided the most stable and effective pH correction, rising from 4.56 to 5.98 by Day 140. This reflects biochar's well-documented buffering capacity, high cation exchange capacity (CEC), and microbial habitat formation (Ahmad *et al*. 2016). Biochar also helped regulate soil temperature, maintaining it within a narrow range of 30 to 32.3 °C, reflecting its thermal insulating properties. Its addition significantly lowered thermal conductivity and diffusivity, while only slightly affecting heat capacity (Usowicz *et al*. 2020). These optimal root-zone conditions supported the most balanced growth across all parameters, with 25 leaves, 21.8 cm leaf length, 40.0 cm stem length, and the largest stem diameter (0.82 cm). Although T4 consistently recorded the highest NDVI values (0.90), the differences among treatments were not statistically significant ($P = 0.386$), indicating comparable chlorophyll development across fertilization regimes. The observed trend may reflect improved nutrient availability and root-zone conditions, although no direct causal relationship can be established based on NDVI alone (Salamat *et al*. 2024).

Statistical Analysis

As shown in Table 2, the treatments applied demonstrated significant effects on selected plant morphological traits, particularly number of leaves ($P = 0.046$) and leaf length ($P = 0.038$), indicating that the treatments positively influenced early vegetative growth. Although stem length approached significance ($P = 0.061$), stem diameter and greenness level were unaffected ($P > 0.3$), suggesting that these parameters were less responsive to the treatments within the study period. The weak correlation between soil pH and plant responses ($P = 0.089$) further indicates that pH alone did not adequately capture the effects on plant growth performance. In contrast, leachate COD was strongly affected by treatments ($P = 0.01$), with a substantial effect size ($\omega^2 = 0.389$), indicating clear changes in root exudate profiles and rhizosphere processes. These findings suggest that while the treatments moderately enhanced plant morphological development, they had a more pronounced impact on biochemical interactions in the root zone.

Table 2. Summary of ANOVA and Regression Analyses for Growth Parameters, Soil pH, and Plant Leachate COD in Durian Seedlings

Parameter	Source	Sum of Squares	df	Mean Square	F	P	ω²	Notes
Number of Leaves	Treatment	273.886	3	91.295	2.909	0.046	0.115	Type III SS
	Residuals	1255.273	40	31.382				
Leaf Length (cm)	Treatment	71.741	3	23.914	3.092	0.038	0.125	Type III SS
	Residuals	309.369	40	7.734				
Stem Length (cm)	Treatment	790.377	3	263.459	2.666	0.061	0.102	Type III SS
	Residuals	3953.202	40	98.83				
Stem Diameter (cm)	Treatment	0.067	3	0.022	0.886	0.456	0	Type III SS
	Residuals	1.013	40	0.025				
Greenness Level	Treatment	0.029	3	0.01	1.039	0.386	0.003	Type III SS
	Residuals	0.371	40	0.009				
Soil pH (Regression)	Model M_0	-	1	-	-	0.089	-	pH treatment as predictor
	Model M_1	-	0	-	-	-	-	Confirmation model
COD of Plant Leachate (mg/L)	Treatment	398806	3	132935.3	5.252	0.01	0.389	Type III SS
	Residuals	404970.8	16	25310.68				

*Type III SS = Type III Sum of Squares, used in unbalanced ANOVA designs.
*pH Regression (M_0 and M_1): Linear regression assessing the effect of treatment pH on soil pH.
*ω² = Omega squared, an effect size measure indicating the proportion of variance explained by treatment.

Leaf diameter serves as a key indicator of early structural strength, which is critical in transplant success during field establishment. Thus, it warranted further pairwise comparison using the Post Hoc Tukey's test. For other parameters, the ANOVA results were deemed sufficient to describe treatment effects, as they primarily reflect general vegetative growth rather than specific structural development, eliminating the need for further post hoc analysis. Table 3 shows the Post Hoc Tukey's test results comparing the average leaf diameter of durian seedlings across four fertilization regimes. All pairwise comparisons revealed no significant differences in leaf diameter between treatments ($P_{tukey} > 0.05$). This indicates that both chemical and organic fertilizers had similar effects on leaf diameter under the conditions tested. The lack of significant differences could be due to similar nutrient availability across treatments or the stronger influence of other factors such as water, light, or soil properties. This suggests that organic fertilizers performed comparably to chemical fertilizers in terms of promoting leaf growth, suggesting that organic options may serve as effective alternatives in Durian seedling cultivation.

Table 3. Post Hoc Tukey's Test for Average Leaf Diameter of Durian Seedlings across Four Treatments

Comparison	Mean Difference	SE	df	t	P (Tukey)
Chemical (T1) vs Organic (T2)	-0.077	0.068	40	-1.139	0.668
Chemical (T1) vs Organic (T3)	-0.046	0.068	40	-0.683	0.903
Chemical (T1) vs Organic (T4)	-0.105	0.068	40	-1.554	0.416
Organic (T2) vs Organic (T3)	0.031	0.068	40	0.456	0.968
Organic (T2) vs Organic (T4)	-0.028	0.068	40	-0.415	0.976
Organic (T3) vs Organic (T4)	-0.059	0.068	40	-0.871	0.82
*P-values are adjusted for multiple comparisons (family-wise adjustment across 4 estimates)					

Leaf Symptoms and Implications of Fertilizer Treatments

As illustrated in Fig. 4A, seedlings treated with NPK 15:15:15 exhibited pronounced stress symptoms, including chlorosis, browning, and necrosis along the leaf margins. These symptoms reflect uneven nutrient uptake. This is a well-documented limitation of conventional chemical fertilizers, which primarily supply macronutrients but often neglect essential micronutrients such as magnesium, zinc, and iron, elements critical for chlorophyll synthesis and physiological balance (Ahmed *et al*. 2024). Furthermore, the rapid nutrient release associated with NPK fertilizers frequently leads to salt accumulation in the rhizosphere, contributing to osmotic stress and root impairment. This effect is further amplified by soil acidification, which reduces the availability of phosphorus and magnesium, ultimately compounding plant stress (Huang *et al*. 2023). Consequently, seedlings in Treatment 1 exhibited stunted growth, fewer leaves, and diminished overall health compared to those receiving organic amendments.

In contrast, seedlings subjected to Treatment 2 (see Fig. 4B) displayed a distinct form of stress (leaf wrinkling), resulting from imbalanced water uptake driven by the high organic matter content of the applied fertilizer, derived from laying hen manure and wood dust. While such organic inputs enhance nutrient supply and microbial activity, their rapid decomposition can create hyperosmotic soil conditions, disrupt moisture distribution, and elevate soil temperatures, all of which contribute to physiological stress (Abdul Rahman *et al*. 2021). This reinforces the importance of careful irrigation and application management when using nutrient-rich organic materials.

Seedlings in Treatments 3 and 4 (Fig. 4C and Fig. 4D, respectively) exhibited no visible stress symptoms, indicating the effectiveness of organic fertilization in supporting healthy plant development. Treatment 3, which utilized POME, provided steady nutrient availability that supported consistent leaf development, although its effectiveness may plateau over time due to potential nutrient imbalances during decomposition (Lu *et al*. 2024). As shown in Fig. 4, Treatment 4, which incorporated biochar, displayed more uniformly green leaves with no visible stress symptoms, suggesting improved physiological stability. These differences, while subtle, are visually discernible and may be associated with biochar's influence on soil aeration, water retention, pH buffering, and nutrient availability, which collectively contribute to favorable conditions for seedling growth.

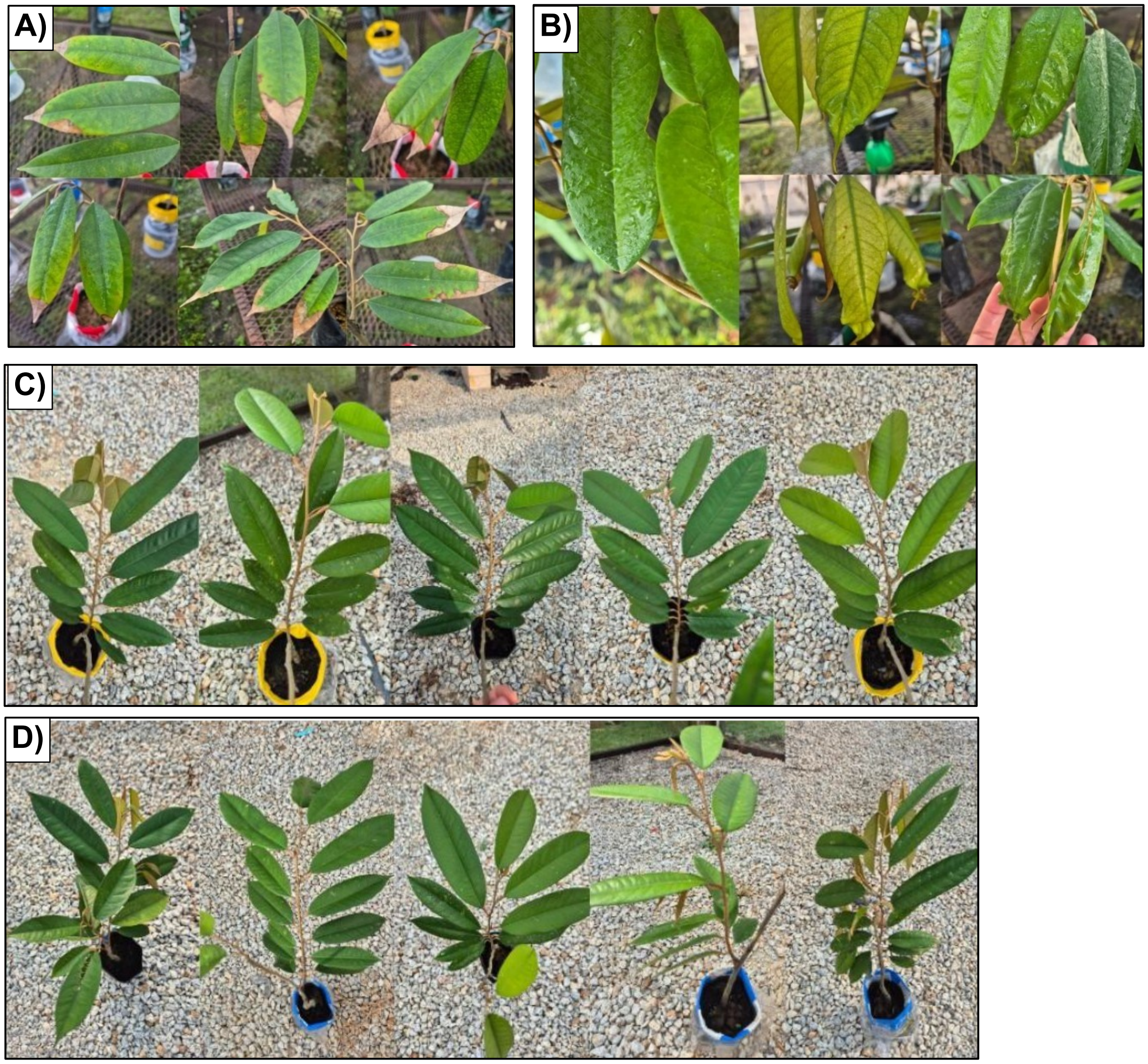

Fig. 4. Leaf conditions of durian seedlings under different fertilization treatments: (A) NPK showing chlorosis and necrosis, (B) manure showing leaf wrinkling, (C) POME showing healthy leaves, and (D) biochar-enriched compost showing more uniform green leaves with no visible stress symptoms

CONCLUSIONS

1. Biochar-enriched compost (T4) significantly enhanced seedling morphometrics, producing 25 leaves, 21.8 ± 1.2 cm leaf length, and 40.0 ± 1.6 cm stem length, nearly double those achieved under chemical fertilizer (T1: 12 leaves, 14.4 ± 0.8 cm, 21.3 ± 1.2 cm) (P = 0.046, P = 0.038). NDVI values also increased to 0.90, exceeding T1 (0.84), indicating improved chlorophyll biosynthesis.
2. Soil quality improved markedly under T4, with pH increasing from 4.56 to 5.98, surpassing the limited adjustment observed in T1 (4.72-5.62). This demonstrates the improved buffering capacity of biochar-enriched formulations in stabilizing soil chemistry.

3. Environmental performance was optimized, as nutrient leaching under T4 was restricted to 153 mg/L COD, significantly lower than manure-based compost (T2: 839 mg/L, P = 0.010). This confirms biochar's dual role in nutrient retention and leachate mitigation, providing a sustainable alternative to conventional fertilizers in durian nurseries.
4. Collectively, this study demonstrated that integrating agronomic and environmental indicators, particularly leachate COD, can provide a more comprehensive framework for evaluating sustainable fertilization strategies in perennial tropical nursery systems.

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