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Comparative Effect of Biochars on the Growth of *Afzelia africana* and *Pterocarpus erinaceus* in Nursery Conditions in Faranah, Guinea

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Authors' contributions

This work was carried out in collaboration among all authors. Author BLD designed the study, wrote the protocol, and drafted the first version of the manuscript. Author HB contributed to the writing of the article and managed the study's analyses. Author AHGA performed the analysis and interpretation of the study results. Author SBD managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Aims: This study aims to assess the effects of various biochar types on the germination, growth, and biomass of two native West African forest species, *Afzelia africana* and *Pterocarpus erinaceus*, under controlled nursery conditions, and to identify suitable biochar treatments for enhancing reforestation practices in Guinea. The study also seeks to provide actionable insights into improving soil resilience and forest growth strategies.

Study Design: Experimental design with five treatment groups.

Place and Duration of Study: Nursery trials conducted at Faranah, Guinea, over a six-month period.

Methodology: Five biochar treatments were applied: straw biochar (BP), peanut shell biochar (BCA), corn stalk biochar (BCM), household waste biochar (BDM), and a control with no biochar (D0). Key parameters measured included germination rate, leaf area, leaflet and leaf counts, as well as fresh and dry biomass for each species. Statistical analyses included normality tests, ANOVA, and Tukey's post-hoc tests, ensuring robust evaluation of treatment effects on measured parameters.

Results: Significant variations were observed across treatments for several growth parameters. *Afzelia africana* responded favorably to BCA and BDM treatments, exhibiting increased leaf area, number of leaves, number of leaflets, and higher fresh and dry biomass ($p < 0.05$). Conversely, *Pterocarpus erinaceus* showed improved germination rate, germination energy, germination speed, and leaf area with the BCM treatment. The findings highlight strong correlations between germination and biomass parameters for *Afzelia africana*, underlining its resilience to substrate variation and the importance of biochar choice.

Conclusion: Tailoring biochar application to species-specific needs can enhance nursery growth conditions for reforestation purposes. BCA and BDM treatments are most beneficial for *Afzelia africana*, while BCM is optimal for *Pterocarpus erinaceus*. These results underline the practical potential of biochar in advancing reforestation initiatives and improving soil management strategies in Guinea's nursery settings.

Keywords: Afzelia africana; biochar; germination; nursery; Pterocarpus erinaceus.

1. INTRODUCTION

The degradation of tropical forests in West Africa is a major environmental issue, exacerbated by the increasing demand for agricultural land and firewood, along with unsustainable management practices (Tyukavina et al., 2018; FAO, 2020). These land use changes lead to significant biodiversity loss and ecosystem service decline, underscoring the urgency of reforestation to restore landscapes and combat soil erosion (Chazdon, 2008; Brancalion & Holl, 2020).

Biochars, produced through the pyrolysis of organic matter, are increasingly used as soil amendments in reforestation initiatives. These materials improve soil fertility and water retention, while also contributing to carbon sequestration (Lehmann & Joseph, 2015; Farag et al., 2024). In West Africa, where soils are often nutrient-poor and vulnerable to erosion, biochar could offer a sustainable solution to support the growth of young plants in nurseries (Sohi et al., 2010; Jeffery et al., 2011). However, few studies have specifically examined the effects of different types of biochars on local forest species such as *Afzelia africana* and *Pterocarpus erinaceus*, two native West African species known for their ecological and economic importance (Louppe et al., 2008; Sanogo et al., 2019).

The application of biochar in nurseries could improve germination rates, growth, and biomass of plants, making the production more vigorous and resilient to environmental stressors (Kammann et al., 2012; Khan et al., 2020). However, the effects of biochars vary depending on the raw materials used for their production, and their effectiveness depends on the specific characteristics of each forest species (Van Zwieten et al., 2010; Mukherjee et al., 2014). A comparative approach using biochars from various sources, such as straw, peanut shells, corn stalks, and organic waste, is thus necessary to identify the most suitable amendments for each species' needs (Schmidt & Wilson, 2014; Nguyen et al., 2021).

The use of biochars as amendments in degraded tropical soils has shown beneficial effects on soil fertility and plant growth (Jeffery et al., 2011). However, the specific adaptation of various biochars to the needs of local forest species remains underexplored, particularly in the African context. This study aims to fill this gap by exploring the interactions between biochar and forest species in nursery conditions, thus providing a scientific basis for improved resource management in reforestation programs (Sohi et al., 2010: Lehmann & Joseph, 2015).

This article aims to evaluate the impact of different biochars on the germination, growth, and biomass of *Afzelia africana* and *Pterocarpus erinaceus*. By identifying the most effective type of biochar for each species, this study will contribute to optimizing reforestation practices in West Africa, offering a potential solution to soil degradation and ecosystem conservation challenges (El-Naggar et al., 2019; Anderson et al., 2022).

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted at the experimental station of the Department of Water, Forests, and Environment of the Valery Giscard d'Estaing Higher Institute of Agronomy and Veterinary Medicine in Faranah (ISAV/F). The station is located between 10°05' North latitude and 10°74' West longitude. Altitude of Faranah 467 m (Fig. 1).

2.2 Plant Material

The plant material consisted of seeds from *Afzelia africana* and *Pterocarpus erinaceus*. These seeds were sown in 1 kg-capacity pots with dimensions of 25 cm x 15 cm, containing different substrate mixtures.

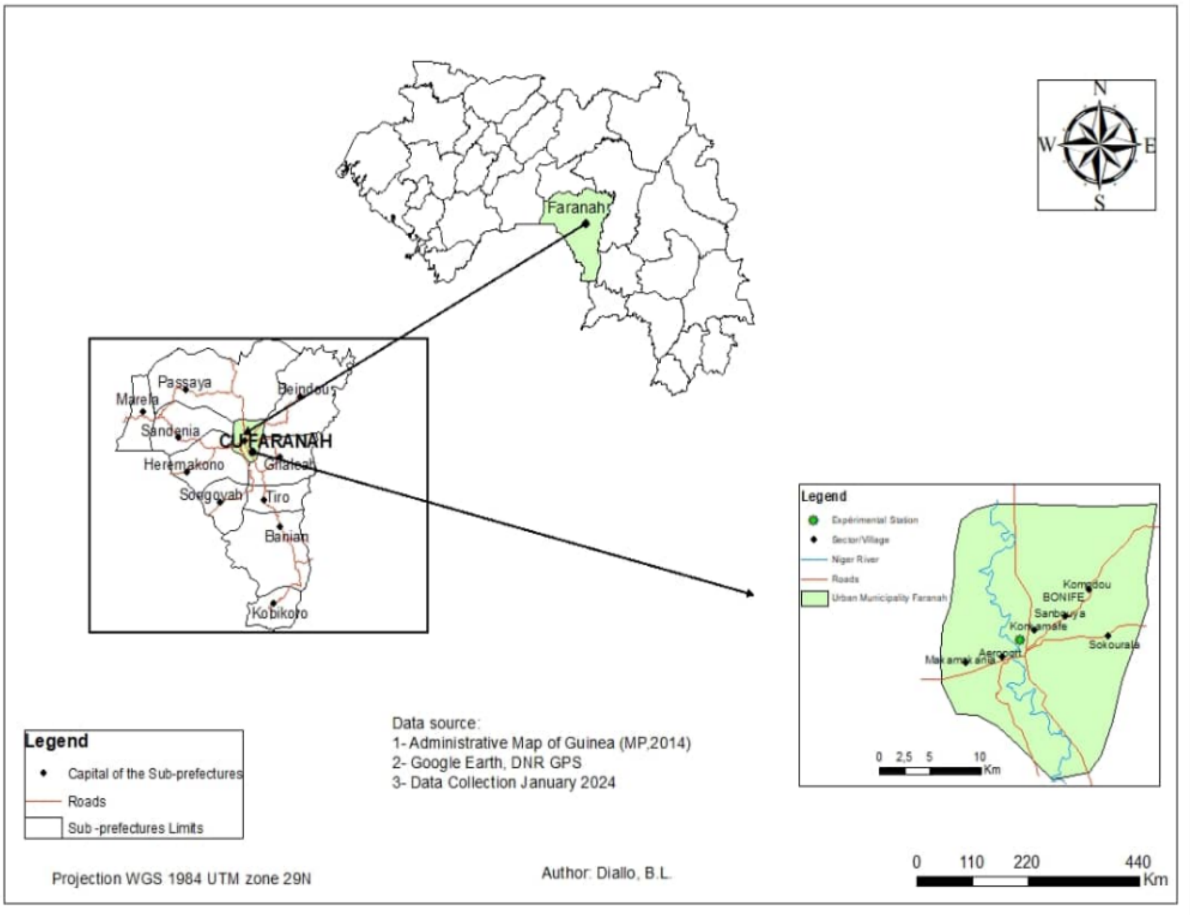

Fig. 1. Map of the Study Area

2.3 Data Collection Methods

2.3.1 Experimental design

The experimental design used was a randomized complete block design (RCBD) with two factors: biochar pretreatment and substrate. Biochar was the primary factor of interest. Each pot contained 650 g of forest soil, 300 g of sand, and 50 g of biochar. The biochar types included straw biochar (BP), peanut shell biochar (BCA), corn stalk biochar (BCM), household waste biochar (BDM), and a control with no biochar (D0).

2.3.2 Seed collection

Seeds of *Afzelia africana* and *Pterocarpus erinaceus* were collected from shrubby fallows east of Faranah, near the Faranah-Bantou road, between February and April 2023, from selected seed-producing trees.

2.3.3 Seed treatment

The outer coverings of *Pterocarpus erinaceus* seeds were trimmed using a pruner, while *Afzelia africana* seeds were directly collected beneath seed-bearing trees. After collection, both seed batches were soaked in ordinary borehole water for 24 hours to break dormancy as a pretreatment. Sowing was then conducted in pots containing a mixture of forest soil, sand, and the various biochar types in the proportions described above.

2.3.4 Measured parameters and employed methods

2.3.4.1 Germination rate

The germination rate was determined from a test using X seeds, where G represents the number of germinated seeds. It was assessed through three parameters. First, the "latent period" or days to first germination, where (d) represents the time between sowing (tg0) and the first germination (tg1). Second, the "germination spread" or duration, where (e) represents the period from the first germination (tg1) to the final germination (tg2). Finally, the germination rate (T) is calculated as the ratio of germinated seeds to the total number of seeds, given by T = G / N * 100 **(**Camara et al., 2023).

2.3.4.2 Germination Speed (Vg)

The germination speed (Vg) is defined as the number of seeds germinated within one-third of the days allotted for germination, essentially representing one-third of the germination potential or germination rate.

Vg = $\frac{n1/_3}{N} X100$;= où n $^1/_3$ = Number of seeds germinated within one-third of the germination time according to Edondoto et al. (2020).

2.3.4.3 Average Plant Height (HMP)

The average height and diameter of the plants were measured over eight months, or 210 days. Measurements for growth parameters, specifically height and diameter, were taken every 15 days, starting from the 28th day after sowing, throughout the eight-month period. A measuring tape was used to measure plant height, and a caliper was used to measure the diameter at the plant collar.

2.3.5 Leaf Area

Leaf area was calculated using the MESURIM software.

2.3.6 Number of leaves and leaflets

These two parameters were counted manually.

2.3.7 Plant biomass evaluation

Biomasses were weighed using a precision scale (0.004 g accuracy) and calculated according to the following formulas: BAH + BRH = BHT; BAS + BRS = BTS.

2.4 Data Analysis Method

To analyze the effects of different types of biochars on the germination, vegetative growth, and biomass of *Afzelia africana* and *Pterocarpus erinaceus*, a rigorous statistical approach was employed. Collected data included germination rate, germination speed, vegetative growth measurements (leaf area, number of leaflets and leaves), and both fresh and dry biomass (aerial, root, and total). These measurements were organized according to the five biochar treatment types: straw biochar, peanut shell biochar, corn stalk biochar, household waste biochar, and a control without biochar.

Prior to comparative analyses, a Shapiro-Wilk normality test was conducted on the data to verify their distribution. A Levene’s test was also applied to assess the homogeneity of variances between treatment groups. These preliminary tests ensured that the data met the required conditions for parametric analyses.

A one-way analysis of variance (ANOVA) was performed for each measured parameter to determine whether the different biochar treatments produced significant effects on germination, vegetative growth, and biomass. When ANOVA indicated a significant difference between groups ($p < 0.05$), a Tukey post-hoc test was applied to identify specific pairs of treatments showing significant differences. This post-hoc test allowed for pairwise comparisons of treatment means, precisely identifying biochars with superior or inferior effects on each measured parameter.

To explore potential relationships between growth and biomass parameters, Pearson correlation analyses were conducted. These analyses aimed to evaluate whether certain germination or growth parameters could predict final biomass or other plant performance indicators. The obtained correlation coefficients measured the strength and direction of relationships and determined whether significant trends existed between measured parameters, such as germination rate and total biomass.

Statistical results were synthesized in tables and graphs, with p-values reported for each analysis to indicate the level of significance. Group means were annotated with distinct letters to mark significant differences between treatments.

The results were interpreted in relation to initial hypotheses and previous studies, identifying the most effective types of biochars for each species based on the analyzed parameters. This methodology thus provided a comprehensive analysis of the effects of different biochars, highlighting their potential applications for reforestation programs in West Africa.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Agrochemical characteristics of biochars

The different biochars are distinguished by their chemical characteristics, potentially influencing plant growth in nurseries. The pH values range from 7.2 (BCM) to 9.1 (BDM). A higher (alkaline) pH can facilitate the absorption of certain nutrients. For example, household waste biochar (BDM), with a pH of 9.1, may benefit plants tolerant to alkaline conditions, such as certain tropical species. The biochars are particularly high in carbon, especially BCA (39.43% C) and BDM (40.48% C), thus increasing organic matter content in the substrate. This richness can enhance water retention and soil stability, which is beneficial for seed germination and initial plant growth. Electrical conductivity (EC) ranges from 0.53 (BP) to 65.7 (BCA), reflecting the potential salinity of the substrate. High EC levels, such as those found in BCA, may sometimes limit growth if plants are sensitive to salts; however, in this case, it appears to favor certain growth metrics for *Afzelia africana* (Table 1).

3.1.2 Germination rate, germination energy, and germination speed

For germination rate and germination speed, species-specific differences are observed depending on the type of biochar. Regarding *Afzelia africana*, germination rates are high for all treatments (76.67% for D0 to 93.33% for BCM), although there are no significant differences ($p=0.323$). This suggests that *Afzelia africana* is well-tolerant of various substrates and biochars. The germination speed is also slightly higher with BCM, indicating that corn stalk-based biochar (BCM) promotes a quicker start to germination, which may be beneficial for reforestation operations requiring vigorous seedlings. In contrast, *Pterocarpus erinaceus* shows increased sensitivity to biochar types, with significant variations in germination rates ($p=0.039$) and germination speed ($p=0.038$). The BCM biochar (83.33%) significantly enhances the germination rate and germination speed compared to other biochars, while the BDM biochar has the lowest effect (56.67%). This demonstrates that *Pterocarpus erinaceus* responds positively to the conditions provided by BCM, possibly due to improved moisture and nutrient retention (Table 2).

Vegetative Growth: Leaf Area, Number of Leaflets, and Number of Leaves Biochars significantly influence vegetative growth parameters for both species, although the effects vary by species. For *Afzelia africana*, regarding leaf area, BDM promotes the largest leaf area (241.28 cm^2), followed by BCA, indicating that biochars derived from household waste and peanut shells optimize leaf growth. This increase could be linked to better water retention and nutrient availability. For the number of leaves and leaflets, BP and BDM support a high number of leaves, with BP yielding the highest (31 leaves). In contrast, BCA produces the highest number of leaflets (177), suggesting this biochar can enhance leaf development in a more qualitative manner.

For *Pterocarpus erinaceus*, leaf area is significantly influenced (p=0.000), with BCM producing the largest area (75.71 cm²). Therefore, BCM is most favorable for maximizing light absorption, enhancing photosynthesis. However, the number of leaves and leaflets does not vary significantly, except that BCA promotes a higher number of leaflets. This may indicate that while the number of leaves remains unchanged, the leaf structure is better developed under BCA influence (Table 3).

Table 1. Agrochemical characteristics of soil and applied Biochars

Paramteres	Soil	Biochars			
		BP	BCA	BCM	BDM
pH (eau)	6,1	7,4	7,6	7,2	9,1
Electrical Conductivity (EC, µs/cm)	8,36	0,53	65,7	1,97	33,3
Carbone (C, %)	2,1	39,43	11,03	40,17	40,48
Total Nitrogen (%)	0,15	0,34	0,76	0,42	0,67
C/N ratio (%)	14	117,35	14,60	95,65	60,24
Organic Matter (%)	3,6	67,82	18,98	69,10	69,63
Available Phosphorus (ppm)	55	1,17	1,09	5,96	4,29
Calcium Ca^{2+} ($cmol.kg^{-1}$)	0,769	nd	nd	nd	nd
Magnésium Mg^{2+} (cmol.kg-1)	0,706	nd	nd	nd	nd
Potassium K^{+} (cmol.kg-1)	0,09	nd	nd	nd	nd
Na^{+} (cmol.kg-1)	0,067	nd	nd	nd	nd
CEC ($cmol.kg^{-1}$)	3,16	nd	nd	nd	nd
Ca (ppm)	nd	1,278	0,688	0,671	4,938
Mg (ppm)	nd	0,311	0,239	0,390	0,181
K (ppm)	nd	0,774	1,260	1,192	3,480
Fe (ppm)	15,26	1,458	2,464	1,088	2,425
Mn (ppm)	43,14	4,237	4,817	3,591	4,151
Cu (ppm)	206	44,361	44,761	37,161	42,561
Zn (ppm)	2,18	0,137	0,137	0,082	0,161

Legend:
pH: hydrogen potential; C/N: Carbon-to-nitrogen ratio; CEC: Cation exchange capacity; BP: Straw-based biochar; BCA: Peanut shell-based biochar; BCM: Corn stalk-based biochar; BDM: Household waste-based biochar; nd: not determined

Table 2. Germination rate, germination energy, and germination speed

Plant Species	Biochars	Germination Rate (%)	Germination Energy (%)	Germination Speed (%)
Afzelia africana	D0	76.67 ± 3.33a	38.33 ± 1.67a	25.56 ± 1.11a
	BP	83.33 ± 3.33a	41.67 ± 1.67a	27.78 ± 1.11a
	BCA	90.00 ± 5.77a	45.00 ± 2.89a	30.00 ± 1.92a
	BCM	93.33 ± 3.33a	46.67 ± 1.67a	31.11 ± 1.11a
	BDM	90.00 ± 10.00a	45.00 ± 5.00a	30.00 ± 3.33a
	P-value	**P=0.323**	**P=0.323**	**P=0.324**
Pterocarpus erinaceus	D0	60.00 ± 5.77b	30.00 ± 2.89b	20.00 ± 1.92b
	BP	60.00 ± 5.77b	30.00 ± 2.89b	20.00 ± 1.92b
	BCA	73.33 ± 8.82ab	36.67 ± 4.41ab	24.44 ± 2.94ab
	BCM	83.33 ± 3.33a	41.67 ± 1.67a	27.78 ± 1.11a
	BDM	56.67 ± 3.33b	28.33 ± 1.67b	18.89 ± 1.11b
	P-value	**P=0.039**	**P=0.039**	**P=0.038**

Note: Values are expressed as mean ± standard deviation. Different letters (a, b) within a column indicate significant differences between treatments at p < 0.05

Table 3. Average values of leaf area, number of leaflets, and number of leaves

Plant Species	Biochars	Leaf Area (cm²)	Number of Leaves	Number of leaflets
Afzelia africana	D0	171.66 ± 1.17e	17.00 ± 0.58c	129.33 ± 0.88d
	BP	174.50 ± 0.61d	31.00 ± 0.58a	166.00 ± 0.58b
	BCA	236.35 ± 0.58b	23.00 ± 0.58b	177.00 ± 0.58a
	BCM	177.84 ± 0.59c	22.33 ± 0.67b	119.33 ± 0.88e
	BDM	241.28 ± 1.11a	24.00 ± 0.58b	150.67 ± 0.88c
	P-value	**P=0.000**	**P=0.000**	**P=0.000**
Pterocarpus erinaceus	D0	54.51 ± 1.07c	10.00 ± 1.15a	24.33 ± 1.20c
	BP	46.48 ± 1.33d	6.67 ± 1.20a	28.67 ± 1.20b
	BCA	46.89 ± 0.69d	10.00 ± 1.15a	39.33 ± 1.45a
	BCM	75.71 ± 0.96a	7.33 ± 1.86a	25.67 ± 1.33bc
	BDM	60.65 ± 1.35b	5.67 ± 2.33a	10.67 ± 1.20d
	P-value	**P=0.000**	**P=0.273**	**P=0.000**

3.1.3 Fresh biomass and dry biomass

Biomass accumulation is essential for assessing plant vigor. Results showed that for *Afzelia africana*, fresh biomass: BCA is particularly effective in increasing aerial fresh biomass (121.05 g), and BCM boosts root biomass (50.25 g), supporting balanced plant development. For dry biomass, BCA remains the most effective biochar, with a maximum total dry biomass (BTS) of 93.92 g, highlighting its positive impact on long-term growth.

In contrast, for *Pterocarpus erinaceus*, differences in biomass (both fresh and dry) between treatments are not significant. This could suggest that this species is less responsive to the enhancements provided by biochars or that the biochars used do not supply the necessary nutrients for optimal growth (Tables 4 and 5).

3.1.4 Correlations between growth parameters

Correlations between parameters provide insights into the relationships among germination, growth, and final biomass, as shown in Tables 6 and 7.

For *Afzelia africana*: (1) The germination rate (TG) is positively correlated with total dry biomass (BST), indicating that a higher germination rate contributes to greater biomass production. (2) Final height (HFinale) and average growth speed (VMC) are also positively correlated with both total fresh and dry biomasses, suggesting that plants growing faster in height also accumulate more biomass. This shows that height can be a good indicator of overall plant health.

For *Pterocarpus erinaceus*: (1) Although correlations are less pronounced for this species, the germination rate is correlated with both total dry biomass (BST) and fresh biomass (BHT), showing a relationship between initial germination success and nursery productivity. (2) Final height and growth speed (VMC) are positively correlated with fresh and dry biomasses, but these relationships are weaker than those for *Afzelia africana*, suggesting that other unmeasured factors may influence the growth of *Pterocarpus erinaceus*.

3.2 Discussion

The results of this study highlighted the effect of different types of biochars on the germination, vegetative growth, and biomass of *Afzelia africana* and *Pterocarpus erinaceus*. The distinct responses observed between the two species, depending on the applied biochars, underscore the importance of selecting amendments suited to the specific needs of forest species. These findings align with prior research emphasizing the variability in biochar effects, which depend on biochar feedstock, soil type, and plant species characteristics (Jeffery et al., 2011; Lehmann & Joseph, 2015).

3.2.1 Effect of biochar on germination rate

The results showed a significant variation in germination rate for *Pterocarpus erinaceus* depending on the biochars, but not for *Afzelia africana*. This difference could be due to the specific substrate requirements of *Pterocarpus erinaceus*. Previous studies have shown that biochars improve germination by increasing nutrient availability and enhancing soil structure (Jeffery et al., 2011; Lehmann & Joseph, 2015). The BCM (corn stalk biochar) and BCA (peanut shell biochar) were particularly effective in promoting germination in this species. These results suggest that the ability of these biochars to enhance moisture retention and nutrient availability played a critical role in activating the germination process (El-Naggar et al., 2019).

In contrast, for *Afzelia africana*, the lack of significant differences between biochar treatments indicated a higher tolerance to substrate variations. This species appeared to benefit from the presence of biochar in general, without requiring a specific type. This species appeared to benefit from the presence of biochar in general, without requiring a specific type. Such adaptability highlights its suitability for reforestation efforts across diverse environmental conditions (Nguyen et al., 2021).

3.2.2 Influence of biochars on vegetative growth (Leaf area, number of leaflets, and number of leaves)

Vegetative growth results showed that household waste biochar (BDM) and peanut shell biochar (BCA) had notable positive effects on leaf area and leaf count for *Afzelia africana.* Biochars with high organic matter and carbon content have been shown to enhance leaf area by improving water retention and nutrient availability (Schmidt & Wilson, 2014; Zhao et al., 2021). The sustained release of nutrients provided by these biochars may have supported continuous vegetative development.

For *Pterocarpus erinaceus*, only leaf area was significantly influenced by biochars, particularly by BCM. This response could be linked to BCM's ability to provide a soil structure

Table 4. Average values of fresh biomass

Plant Species	Biochars	Aerial Fresh Biomass (BAH, g)	Root Fresh Biomass (BRH, g)	Total Fresh Biomass (BHT, g)
Afzelia africana	D0	54.45 ± 0.95d	34.35 ± 1.18c	88.80 ± 1.09c
	BP	82.87 ± 18.39b	39.95 ± 0.84b	122.82 ± 18.42b
	BCA	121.05 ± 1.41a	38.15 ± 1.01b	159.20 ± 1.26a
	BCM	82.20 ± 1.50b	50.25 ± 1.13a	132.45 ± 1.35ab
	BDM	97.50 ± 0.75ab	52.25 ± 0.20a	149.75 ± 0.67ab
	P-value	**P=0.003**	**P=0.000**	**P=0.001**
Pterocarpus erinaceus	D0	2.93 ± 0.93a	5.97 ± 2.09a	8.90 ± 3.00a
	BP	3.30 ± 0.46a	6.67 ± 0.79a	9.97 ± 1.23a
	BCA	3.20 ± 0.83a	5.97 ± 1.87a	9.17 ± 2.70a
	BCM	4.03 ± 1.39a	6.40 ± 0.62a	10.43 ± 2.01a
	BDM	2.63 ± 1.29a	6.20 ± 1.42a	8.83 ± 2.68a
	P-value	**P=0.900**	**P=0.996**	**P=0.985**

Legend: BAH: Aerial Fresh Biomass, BRH: Root Fresh Biomass, BHT: Total Fresh Biomass

Table 5. Average values of dry biomass

Plant Species	Biochars	Aerial Dry Biomass (BAS, g)	Root Dry Biomass (BRS, g)	Total Dry Biomass (BST, g)
Afzelia africana	D0	26.60 ± 0.92d	23.75 ± 1.01b	50.35 ± 0.09d
	BP	56.45 ± 0.55b	31.20 ± 1.10a	87.65 ± 0.55b
	BCA	60.37 ± 1.67a	33.55 ± 1.18a	93.92 ± 0.87a
	BCM	50.30 ± 1.50c	31.30 ± 1.33a	81.60 ± 2.45c
	BDM	55.55 ± 1.33b	29.85 ± 0.95a	85.40 ± 2.08bc
	P-value	**P=0.000**	**P=0.001**	**P=0.000**
Pterocarpus erinaceus	D0	1.57 ± 0.52a	2.73 ± 1.03a	4.30 ± 1.55a
	BP	1.80 ± 0.25a	2.93 ± 0.27a	4.73 ± 0.52a
	BCA	1.87 ± 0.69a	2.93 ± 1.34a	4.80 ± 2.03a
	BCM	2.27 ± 0.88a	4.03 ± 1.08a	6.30 ± 1.96a
	BDM	1.53 ± 0.73a	2.10 ± 0.95a	3.63 ± 1.68a
	P-value	**P=0.930**	**P=0.748**	**P=0.833**

Legend: BAS: Aerial Dry Biomass, BRS: Root Dry Biomass, BST: Total Dry Biomass

Table 6. Correlation between evaluated parameters of *Afzelia africana* in nursery conditions under different types of biochars

	TG	VG	Hi	Hf	VMC	Di	Df	SF	NFO	NFE	BAH	BRH	BHT	BAS	BRS	BTS
TG	1															
VG	1,000**	1														
Hi	0,092	0,092	1													
Hf	0,337	0,337	-,055	1												
VMC	0,198	0,198	-,643**	,764**	1											
Di	-0,058	-0,057	-0,270	0,017	0,098	1										
Df	0,245	0,245	0,118	-,061	-0,102	-0,164	1									
SF	0,315	0,315	0,445	,231	-0,150	-0,353	-0,243	1								
NFO	0,198	0,198	0,075	,056	0,052	-0,159	0,398	-0,030	1							
NFE	0,106	0,106	0,323	,532*	0,317	-0,097	-0,127	0,031	0,267	1						
BAH	0,412	0,412	0,318	,463	0,101	-0,278	-0,218	0,725**	-0,045	0,315	1					
BRH	0,469	0,469	-0,108	,466	0,442	-0,129	0,193	0,322	0,109	0,188	0,213	1				
BHT	0,499	0,499	0,262	,544*	0,209	-0,287	-0,148	0,745**	-0,012	0,33 7	0,966**	0,456	1			
BAS	0,502	0,502	0,366	,701**	0,332	-0,096	-0,149	0,571*	0,142	0,706**	0,757**	0,433	0,803**	1		
BRS	0,509	0,509	0,316	,683**	0,305	,0203	-0,241	0,414	-0,006	0,545*	0,691**	0,350	0,721**	0,840**	1	
BTS	0,519*	0,519*	0,365	,718**	0,336	-0,028	-0,175	0,551*	0,111	0,689**	0,764**	0,426	0,807**	0,992**	0,903**	1

**. Correlation is significant at the 0.05 level (two-tailed), ** correlation is significant at the 0.01 level (two-tailed). TG: Germination Rate, VG: Germination Speed, Hi: Initial Height, Hf: Final Height, VMC: Average Growth Speed, Di: Initial Diameter, Df: Final Diameter, SF: Leaf Area, NFO: Number of Leaflets, NFE: Number of Leaves, BAH: Aerial Fresh Biomass, BRH: Root Fresh Biomass, BHT: Total Fresh Biomass, BAS: Aerial Dry Biomass, BRS: Root Dry Biomass, BTS: Total Dry Biomass*

Table 7. Correlation between evaluated parameters of *Pterocarpus erinaceus* in nursery conditions under different types of biochars

	TG	VG	Hi	Hf	VMC	Di	Df	SF	NFO	NFE	BAH	BRH	BHT	BAS	BRS	BTS
TG	1															
VG	1,00**	1														
Hi	0,08	0,083	1													
Hf	0,18	0,178	0,258	1												
VMC	0,18	0,179	-0,134	,886**	1											
Di	-0,1	-0,102	0,577*	0,018	-0,289	1										
Df	0,3	0,299	0,175	0,305	0,187	0,075	1									
SF	0,43	0,432	-0,023	-0,072	-0,024	0,033	0,253	1								
NFO	0,31	0,31	0	0,418	0,464	-0,389	-0,152	-0,436	1							
NFE	0,01	0,012	-0,508	0,105	0,383	-0,508	-0,229	-0,244	,520*	1						
BAH	0,24	0,237	0,415	0,512	0,333	0,064	0,489	0,172	0,127	-0,028	1					
BRH	0,02	0,019	0,32	0,413	0,281	0,236	0,174	0,01	-0,023	0,009	0,809**	1				
BHT	0,12	0,117	0,378	0,478	0,318	0,171	0,322	0,082	0,042	-0,007	0,934**	,966**	1			
BAS	0,19	0,189	0,44	0,578*	0,386	0,113	0,499	0,159	0,13	-0,009	0,986**	,821**	,935**	1		
BRS	0,22	0,223	0,36	0,5	0,382	0,02	0,365	0,203	0,198	0,113	0,943**	,852**	,935**	,956**	1	
BTS	0,21	0,212	0,395	0,535*	0,388	0,056	0,42	0,188	0,174	0,067	0,970**	,849**	,945**	,983**	,993**	1

**. Correlation is significant at the 0.05 level (two-tailed), ** Correlation is significant at the 0.01 level (two-tailed). TG: Germination Rate, VG: Germination Speed, Hi: Initial Height, Hf: Final Height, VMC: Average Growth Speed, Di: Initial Diameter, Df: Final Diameter, SF: Leaf Area, NFO: Number of Leaflets, NFE: Number of Leaves, BAH: Aerial Fresh Biomass, BRH: Root Fresh Biomass, BHT: Total Fresh Biomass, BAS: Aerial Dry Biomass, BRS: Root Dry Biomass, BTS: Total Dry Biomass* that facilitates nutrient absorption while maintaining adequate moisture (Nguyen et al., 2021). However, leaf count and leaflet count did not vary significantly, suggesting that *Pterocarpus erinaceus* prioritized leaf expansion over leaflet density in nutrient-rich conditions. These results emphasize the need for species-specific biochar applications to optimize vegetative growth.

3.2.3 Biomass accumulation: fresh and dry biomass

For *Afzelia africana*, BCA and BCM biochars were distinguished by their positive effect on total biomass, with high values for both fresh and dry biomass. Previous studies indicate that biochars improve nutrient retention capacity, particularly in nutrient-poor soils, which supports biomass production in woody species (Lehmann & Joseph, 2015; Anderson et al., 2022). The ability of biochars to enhance microbial activity and soil carbon may have further contributed to these outcomes (El-Naggar et al., 2019).

In contrast for *Pterocarpus erinaceus*, biomass differences between biochars were not significant, suggesting that this species responded less to biochar inputs in terms of biomass production. This suggests that this species may be less responsive to biochar inputs or that its growth relies more on other amendments or environmental factors (Meyer et al. 2018; Smith et al., 2020). Such findings highlight the complexity of biochar-soil-plant interactions and the importance of considering species-specific nutrient requirements in biochar applications.

3.2.4 Correlations between growth parameters

Correlations showed that, for *Afzelia africana*, germination rate and germination speed were positively associated with total biomass. High germination rates often translate to optimal growth and biomass accumulation, making early-stage performance a strong indicator of overall success (El-Naggar et al., 2019; Githinji, 2019). This correlation underscores the importance of biochar amendments in enhancing early growth stages, particularly for species responsive to nutrient enrichment.

For *Pterocarpus erinaceus*, correlations between leaf area and biomass were weak, indicating that this species could develop biomass independently of leaf area, likely due to differential allocation of resources between aboveground and belowground growth. Future studies should investigate root biomass and root-to-shoot ratios to better understand the role of biochars in promoting belowground development for this species (Zwart & Kuikman, 2019; Nguyen et al., 2021; Inyang et al., 2020).

4. CONCLUSION

In summary, this study highlights the differential effects of biochars on two key forest species. *Afzelia africana* showed significant benefits from BCA biochar, including increased leaf area, aerial and root biomass, and overall growth, making BCA a promising choice for reforestation projects involving this species. In contrast, *Pterocarpus erinaceus* exhibited a more modest response to biochars, but BCM improved germination and leaf area, suggesting its suitability for maximizing initial establishment in nurseries.

These findings emphasize that biochar selection should be tailored to the plant species and growth objectives. For *Afzelia africana*, BCA is recommended to enhance growth and biomass production, while for *Pterocarpus erinaceus*, BCM is preferable for seedlings due to its positive effects on germination and leaf development. By guiding nursery practices, these insights could contribute to improving the survival and growth rates of forest species, supporting more effective and sustainable reforestation efforts.

While these findings offer valuable insights into the role of biochars in enhancing the growth and establishment of forest species, certain limitations must be acknowledged, and further research is needed to build on these results and explore new avenues

5. LIMITATIONS

This study has certain limitations that should be acknowledged. First, the experiments were conducted under controlled nursery conditions, which may not fully replicate the complexity of natural environments. Factors such as climate variability and interactions with other organisms were not considered, even though they may influence the effectiveness of biochars. Second, the study focused on two species, *Afzelia africana* and *Pterocarpus erinaceus*, which limits the generalizability of the findings to other forest species. Finally, the long-term effects of biochar application on soil properties and plant growth were not assessed, warranting further investigation.

6. PERSPECTIVES

To address these limitations, future research should evaluate the performance of BCA and BCM biochars under field conditions across various soil types and ecological zones. Long-term studies could also assess the durability of biochar benefits and their impact on soil properties over time. Furthermore, expanding the scope to include additional forest species could provide broader insights into the compatibility of biochars with diverse reforestation initiatives. Finally, exploring the economic feasibility and sustainability of large-scale biochar production would support its practical application in extensive reforestation projects.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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