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RESEARCH ARTICLE

Innovative silvicultural strategies for sustainable Casuarina hybrid plantation and bioenergy production

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Abstract

This study explored the potential of Casuarina hybrid clone (A-01) as a promising energy crop for dendro-energy plantations, focusing on optimizing silvicultural practices like spacing and biochar application. Energy plantations, designed to produce high biomass on short rotations, play a critical role in sustainable energy solutions by providing renewable raw materials for bioenergy and reducing dependence on fossil fuels. Casuarina species, known for their adaptability to varied soil and climatic conditions, fast growth and high biomass yield, are increasingly favoured for such purposes. The Casuarina hybrid further enhances these traits, offering improved growth rates, higher wood calorific values and potential benefits in soil health and carbon sequestration. The study was conducted by establishing a research plantation trial at a farmer's field in Coimbatore, India, from December 2023 to August 2024, the experiment utilized a split-plot design over 0.4 acres, featuring five spacing treatments (1 m × 0.5 m, 1 m × 1 m, 1 m × 1.5 m, 1.5 m × 1.5 m and 2 m × 2 m) as main plots and four biochar levels (0, 1, 2 and 3 kg/plant) as subplots, with three replications. Key findings included a maximum survival rate (100 %) under combinations A1B3, A2B2 and A4B3. Plant height after six months ranged from 277.4 cm to 416.8 cm, with the tallest plants observed in A2B4. The largest collar diameter (5.01 cm) and highest biomass (5886.8 g) were recorded in A2B4 and A2B2, respectively, while the lowest biomass (2496.6 g) was associated with A3B1. The study demonstrated the synergistic effects of optimized spacing and biochar application on the growth, biomass production and soil enhancement of Casuarina hybrid, offering valuable insights for its potential as an energy crop.

Keywords: biochar application; casuarina hybrid clone; dendro-energy; energy plantation; silvicultural practices; spacing

Introduction

India, as the third-largest global energy consumer, is at a pivotal juncture in addressing its growing energy demands while striving to reduce its carbon footprint. With electricity consumption projected to grow at 6.1 % annually in 2024, surpassing Japan and Korea combined, India must pivot toward sustainable energy solutions. Renewable energy and bioenergy are central to achieving India's climate targets, which include a 50 % share of renewable energy by 2030, reducing carbon emissions by 1 billion tonnes and reaching net -zero emissions by 2070.

Biochar, a carbon-rich material produced through pyrolysis of organic biomass, has emerged as a promising tool for both soil enhancement and climate change mitigation (1). Biochar production involves thermo-chemical processes at 350 °C to 600 °C, creating a porous structure with a large surface area that enhances soil fertility, water retention and microbial activity (2). It sequesters carbon for centuries, contributing to climate goals while benefiting soil health. Wood-based biochar, derived from residues like sawdust and wood chips, is particularly effective for nutrient retention, microbial population stimulation and long-term soil structure stabilization (3, 4).

Despite its initial role in energy production and pollutant adsorption (5), biochar is now recognized for its pivotal role in agriculture. It addresses soil degradation, especially in low-fertility and acidic soils, by enhancing nutrient cycling, stabilizing aggregates and promoting microbial enzyme activity. However, initial nutrient immobilization may temporarily limit plant growth, which is mitigated over time with consistent application (6).

Dendro-energy plantations, particularly those involving Casuarina hybrid, align with India's bioenergy objectives. Casuarina hybrid, a fast-growing, nitrogen-fixing tree species, offers high biomass yields under diverse soil and climatic conditions. Its potential as an energy crop is amplified by short rotation cycles (5-7 years) and its suitability for degraded or saline soils. With a calorific value of 4500 kcal/kg, it provides a sustainable alternative to fossil fuels and contributes to soil improvement and erosion control.

This study aims to address these gaps by systematically evaluating the effects of biochar application and variable spacings on the growth and biomass production of Casuarina hybrid plantations. By optimizing these factors, this research contributes for establishing Casuarina hybrid as a cornerstone of India's bioenergy initiatives, supporting sustainable development and climate goals.

Materials and Methods

Study area

The present experiment was carried out in farmer's field, in Syndicate Pvt. Ltd. Industrial site, Coimbatore dist., Tamil Nadu in December 2024. Geographically, the experimental site is situated at 11° 17'32.0" N latitude and 76° 58'38.2" E longitude situated in the semi-arid region of southern India. The climate of the study area is characterized by warm, temperate to sub-tropical rainy season with good tropical sunshine. The maximum temperature in the site during the study period ranged from 25.9 °C - 37.5 °C and the minimum temperature ranged from 16.9 °C - 22.6 °C (Fig. 1). The mean annual rainfall ranges between 0.1 mm - 269.0 mm. The soil of the experimental site was sandy loam in texture, low in organic carbon and available nitrogen, medium in available phosphorus and high in available potassium. The initial soil samples were analyzed and found pH as 6.4, EC 0.63 dSm^{-1}, OC 0.55 %, available N 180.2 kg ha^{-1}, available P - 9.36 kg ha^{-1} and available K 146.4 kg ha^{-1} at a depth of 0-30 cm.

Methodology

The study aimed to estimate the biomass of a *Casuarina equisetifolia* hybrid plantation under different spacing and biochar dose treatments. The study was conducted between November 2023 and August 2024 to evaluate the impact of different spacings and biochar doses on the biomass of a Casuarina hybrid plantation (Table 1-3). The experiment followed a split-plot design with five main treatments and four sub-treatments, replicated three times. A total of 48 subplots, each consisting of 12 plants, were established, as detailed in the experimental layout Fig. 2, 3. Initial soil properties were assessed prior to plantation establishment.

Biochar with a pH of 9.71, produced via slow pyrolysis of mixed short-rotation tree species, was procured from an industry. Quality planting stock was prepared from vegetative cuttings of elite hybrid mother trees treated with IBA 1000 ppm and grown in a potting mixture of sand, soil and FYM (2:1:1 ratio). Four to five-month-old seedlings were used for the study. Standard fertilization, including recommended dose of Diammonium Phosphate (DAP), was applied initially and as recommended throughout the study period.

Growth assessment was conducted at two-month intervals, expressed as Months After Planting (MAP), throughout the study period. Biometric traits, including plant height, collar diameter, number of branches, sturdiness quotient, volume and biomass, were observed and recorded. Plant height was measured from the ground level to the terminal tip using a measuring staff or scale, expressed in centimetres. Collar diameter was assessed at the seedling's collar region using a digital calliper, with measurements recorded in millimetres and expressed in centimetres. The number of branches was counted manually on sample trees. The sturdiness quotient, an indicator of plant stability, was calculated as the ratio of shoot length to collar diameter. Volume index (cm^3) was determined using the formula Height (cm) × Collar Diameter^2 (cm^2) (7). Biomass estimation was conducted using a non-destructive method, where biomass (g/tree) was calculated as the product of the volume (cm^3) and wood-specific gravity. Data collected were analysed statistically to evaluate the impact of biochar doses and spacing on the growth and biomass production of the plantation.

Table 1. Details of the experiment

Tree Species	*Casuarina* hybrid
Design of experiment	Split plot
Replication	3
Treatments	Factor 1: Planting densities Factor 2: Doses of biochar application
Time of planting	December, 2023
Site	Industrial Site (Jadayampalayam)
Area	0.4 acres

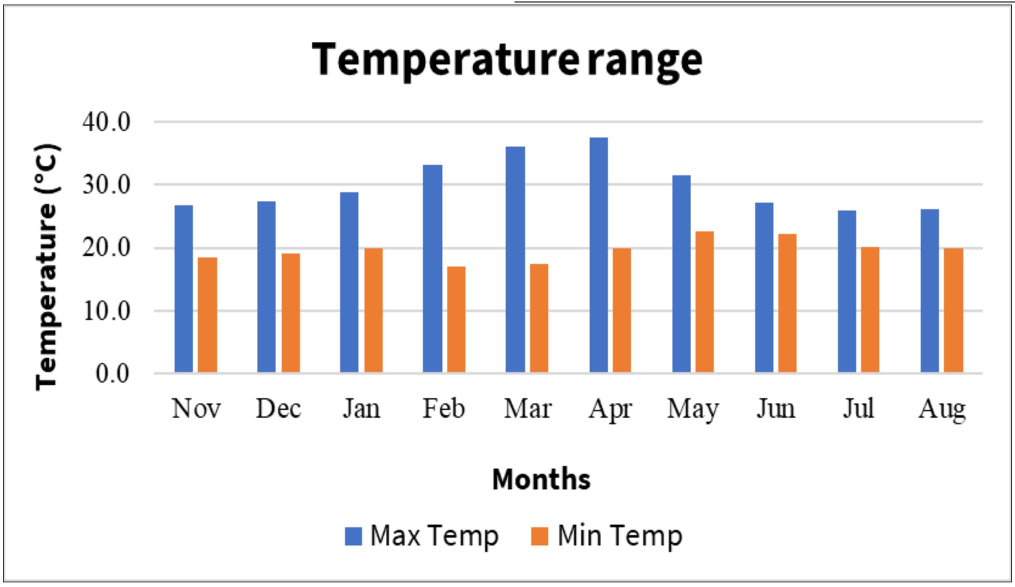

Fig. 1. Temperature of the study area.

Table 2. Details of the main treatments

MAIN TREATMENT	PLANTING DENSITY (m×m)
A1	1×0.5
A2	1×1
A3	1×1.5
A4	1.5×1.5
A5	2×2

Table 3. Details of the biochar application

SUB TREATMENT	BIOCHAR DOSES (kg/plant)
B1	0
B2	1
B3	2
B4	3

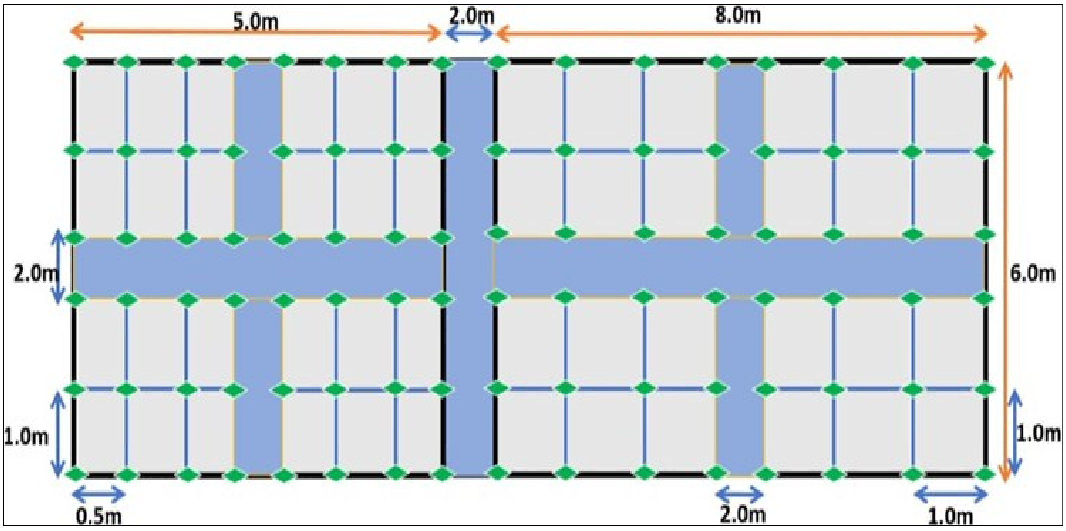

Fig. 2. Layout of 2 Main Plots (A_1 and A_2).

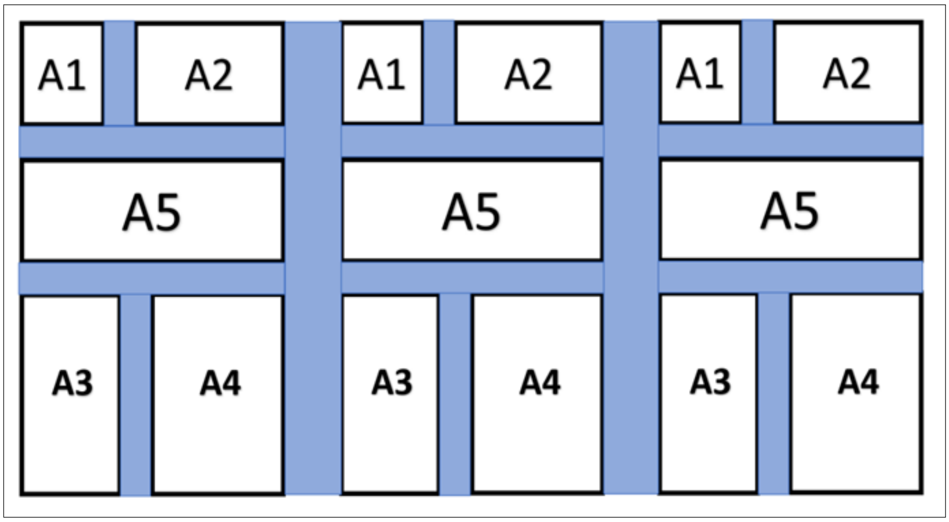

Fig. 3. Layout of the plantation.

Statistical analysis

The data were analyzed using OPSTAT, WASP 2.0, SPSS and Origin Pro software through a two-way analysis of variance (ANOVA) for split-plot design, with tree spacing treatments as the main plot factor and biochar doses as the subplot factor. When the F-test indicated significance, treatment differences were evaluated using the Least Significant Difference (LSD) test at 5 % significance level.

Results

Survival percentage

The survival percentage varied significantly across treatments (Table 4). A 100 % survival rate was observed in A1B3 (1 m × 0.5 m spacing, 2 kg biochar/plant), A2B2 (1 m × 1 m spacing, 1 kg biochar/plant) and A4B3 (1.5 m × 1.5 m spacing, 2 kg biochar/plant). The lowest rates occurred in A4B2 (1.5 m × 1.5 m spacing, 1 kg biochar/plant) and A3B4 (1 m × 1.5 m spacing, 3 kg biochar/plant). Among spacing treatments, A1 (1 m × 0.5 m) had the highest survival (96 %), while A4 (1.5 m × 1.5 m) and A3 (1 m × 1.5 m) were lowest (90 %). At the biochar level, B3 (2 kg biochar/plant) achieved 98.1 %, outperforming B1 (no biochar) and B4 (3 kg biochar/plant). All differences were significant at the 5 % level ($p < 0.05$).

Plant height

Plant height significantly varied at 2 and 6 MAP. At 2 MAP, A1B2 (1 m × 0.5 m spacing, 1 kg biochar/plant) had the tallest plants (69.2 cm), while A3B4 (1 m × 1.5 m spacing, 3 kg biochar/plant) was the shortest (49.6 cm). By 6 MAP, A2B2 (1 m × 1 m spacing, 1 kg biochar/plant) recorded the tallest plants (416.8 cm), whereas A3B1 (1 m × 1.5 m spacing, no biochar) was the shortest (277.4 cm). Significant differences were observed at 2 and 6 MAP ($p < 0.05$), while differences at the initial stage and 4 MAP were not significant (Table 5-7).

Table 4. Effect of spacing and biochar application on survival percentage

Biochar doses (kg/plant) Spacing level (m*m)	Survival percentage					
	B1 (0)	B2 (1)	B3 (2)	B4 (3)	Mean	Main effects (spacing)
A₁ (1 m × 0.5 m)	98.0 ± 0.707^{a}	93.0 ± 2.121^{b}	100.0 ± 0.00^{a}	93.0 ± 1.414^{b}	96.0	96.0^{A}
A₂ (1 m × 1 m)	92.3 ± 0.1.780^{b}	100.0 ± 0.00^{a}	98.3 ± 0.408^{a}	87.3 ± 1.780^{c}	94.5	94.5^{B}
A₃ (1 m × 1.5 m)	88.7 ± 1.780^{c}	93.0 ± 1.414^{b}	99.7 ± 0.408^{a}	86.3 ± 1.780^{d}	91.9	91.9^{C}
A₄ (1.5 m × 1.5 m)	86.7 ± 1.472^{c}	80.0 ± 1.414^{d}	100.0 ± 0.00^{a}	93.3 ± 1.780^{b}	90.0	90.0^{C}
A₅ (2 m × 2 m)	87.0 ± 2.123^{c}	99.0 ± 0.707^{a}	92.7 ± 1.472^{b}	97.0 ± 1.871^{a}	93.9	93.9^{B}
Mean	90.5	93.0	98.1	91.4		93.3
Main effects (biochar doses)	90.5^{C}	93.0^{B}	98.1^{A}	91.4^{C}		93.3

	A	B	A at B	B at A
SE(d)	0.902	0.713	1.53	1.502
CD(p=0.05)	1.859	1.455	3.253	3.142

Table 5. Effect of spacing and biochar application on plant height (cm)

Treatment combinations	Initial	2 MAP	4 MAP	6 MAP
A1B1	68.0 ± 0.630	111.4 ± 1.243^{b}	190.66 ± 3.682	323.8 ± 0.648^{fg}
A1B2	69.2 ± 0.865	117.4 ± 0.403^{a}	191.2 ± 1.616	308.8 ± 1.271^{fgh}
A1B3	62.6 ± 0.130	105.8 ± 1.048^{c}	189.08 ± 0.391	339.6 ± 2.977^{ef}
A1B4	63.8 ± 0.874	104 ± 1.671^{c}	176.06 ± 2.306	297.8 ± 5.753^{gh}
A2B1	60.6 ± 1.017	104.4 ± 1.935^{c}	186.96 ± 3.568	336.4 ± 2.760^{ef}
A2B2	51.2 ± 0.312	98.4 ± 1.268^{d}	198.96 ± 2.477	416.8 ± 3.054^{a}
A2B3	56.4 ± 0.464	100.2 ± 0.068^{d}	197.02 ± 1.374	401.6 ± 5.222^{bc}
A2B4	50 ± 0.558	94.4 ± 1.693^{e}	196.06 ± 0.326	397.2 ± 0.352^{bc}
A3B1	53.2 ± 0.420	88.6 ± 1.659^{f}	159.78 ± 2.110	277.4 ± 2.245^{h}
A3B2	63.4 ± 0.352	102 ± 1.969^{c}	175.04 ± 2.663	306.2 ± 3.316^{gh}
A3B3	61 ± 0.603	97.4 ± 1.095^{c}	165.96 ± 3.267	289.6 ± 4.816^{h}
A3B4	49.6 ± 0.169	81.8 ± 1.070^{g}	158.4 ± 1.084	331.8 ± 4.239^{ef}
A4B1	55.8 ± 0.142	97.2 ± 0.505^{c}	185.78 ± 3.636	359 ± 2.721^{de}
A4B2	52.6 ± 0.829	88.4 ± 0.726^{f}	167.74 ± 1.233	327.2 ± 5.367^{fg}
A4B3	50.6 ± 0.666	83.4 ± 1.312^{g}	160.02 ± 0.387	319.2 ± 1.137^{fg}
A4B4	57.4 ± 0.992	93.2 ± 0.013^{e}	170.7 ± 3.218	318.2 ± 6.062^{fg}
A5B1	60.8 ± 0.848	97.6 ± 0.115^{d}	171.2 ± 1.859	306.6 ± 3.603^{g}
A5B2	58 ± 0.389	100.8 ± 1.612^{d}	187.34 ± 2.861	378.2 ± 7.614^{cd}
A5B3	63.8 ± 0.559	102 ± 0.853^{d}	190.72 ± 2.030	381.6 ± 1.168^{cd}
A5B4	57 ± 0.076	111.6 ± 0.161^{b}	188.5 ± 3.733	372.8 ± 3.723^{cd}
SE (d)	NS	3.903	NS	14.65
CD(P=0.05)		8.264		31.185

Table 6. Effect of spacing and biochar application on plant height at main treatments

Main Treatment mean	Initial (cm)	2 MAP (cm)	4 MAP (cm)	6 MAP (cm)
A₁ (1 m × 0.5 m)	65.9	109.7^{A}	186.8^{A}	317.5^{C}
A₂ (1 m × 1 m)	55.6	99.4^{B}	194.8^{A}	388.0^{A}
A₃ (1 m × 1.5 m)	56.8	92.5^{C}	164.8^{B}	301.3^{D}
A₄ (1.5 m × 1.5 m)	54.1	90.6^{C}	171.1^{B}	330.9^{C}
A₅ (2 m × 2 m)	59.9	103.0^{B}	184.4^{A}	359.8^{B}
SE (d)		1.826	4.591	7.505
CD (p=0.05)	NS	4.277	10.75	17.576

Table 7. Effect of spacing and biochar application on plant height at sub treatments

Sub Treatment mean	Initial (cm)	2 MAP (cm)	4 MAP (cm)	6 MAP (cm)
B₁ (0 kg BC/plant)	59.7	99.8	178.9	320.6^{B}
B₂ (1 kg BC/plant)	58.9	101.4	183.5	343.5^{A}
B₃ (2 kg BC/plant)	57.9	97.8	180.9	346.3^{A}
B₄ (3 kg BC/plant)	55.6	96.0	177.1	347.5^{A}
SE (d)	NS			6.499
CD (p=0.05)		NS	NS	13.337

Collar diameter

Collar diameter showed significant variation among treatments at different stages. At 2 MAP, the largest collar diameter (1.08 cm) was observed in A1B2 (1 m × 0.5 m spacing, 1 kg biochar/plant) and the smallest (0.58 cm) was recorded in A3B4 (1 m × 1.5 m spacing, 3 kg biochar/plant). At 6 MAP, A2B4 (1 m × 1 m spacing, 3 kg biochar/plant) achieved the largest diameter (5.01 cm), while the smallest (2.46 cm) was in A3B1 (1 m × 1.5 m spacing, no biochar). Main plot spacing effects showed maximum diameter under A2 (1 m × 1 m spacing), while subplot treatments revealed the highest diameter with B4 (3 kg biochar/plant) at 6 MAP. All variations were significant ($p < 0.05$) as given in (Table 8-10).

Number of branches

The number of branches increased with time and varied significantly at 6 MAP. Initially, the highest branch count (11) was observed in A1B2 and A2B3 (1 kg or 2 kg biochar/plant), while the lowest (5) occurred in several combinations. At 6 MAP, A1B3 (1 m × 0.5 m spacing, 2 kg biochar/plant) recorded the most branches (43), while A3B4 (1 m × 1.5 m spacing, 3 kg biochar/plant) had the least (27). Spacing and biochar treatments demonstrated significant effects on branch development only at 6 MAP (Table 11-13).

Sturdiness quotient

Sturdiness quotient varied among treatments, showing significant differences at later stages (2-6 MAP). At 6 MAP, the highest quotient (388) was observed with B2 (1 kg biochar/plant), while the lowest (301.3) occurred in B3 (2 kg biochar/plant). Main plot effects revealed maximum sturdiness under A4 (1.5 m × 1.5 m spacing) and minimum under A5 (2 m × 2 m spacing). The data indicated a stronger effect of biochar at moderate doses on plant sturdiness (Table 14-16).

Volume index

The volume index varied significantly across treatments at different stages of measurement (Table 17-19). At 2 MAP, the highest volume (118.49 cm^3) was recorded in A5B4 (2 m × 2 m spacing, 3 kg biochar/plant), while the lowest (23.0 cm^3) was observed in A3B4 (1 m × 1.5 m spacing, 3 kg biochar/plant). By 6 MAP, the maximum volume (8291.3 cm^3) was achieved in A2B2 (1 m × 1 m spacing, 1 kg biochar/plant) and the minimum (3516.4 cm^3) occurred in A3B1 (1 m × 1.5 m spacing, no biochar). Spacing treatments showed maximum volume under A2 (1 m × 1 m), while biochar treatments revealed the highest values with B3 (2 kg biochar/plant). Significant differences were observed at 2 MAP, 4 MAP and 6 MAP ($p < 0.05$).

Table 8. Effect of spacing and biochar application on plant collar diameter (cm)

Treatment combinations	Initial	2 MAP	4 MAP	6 MAP
A1B1	0.46 ± 0.005^{bc}	1.03 ± 0.014^{bcd}	1.38 ± 0.024^{efgh}	3.34 ± 0.026
A1B2	0.52 ± 0.002^{a}	1.08 ± 0.013^{ab}	1.43 ± 0.028^{defg}	3.41 ± 0.023
A1B3	0.39 ± 0.004^{ef}	0.92 ± 0.007^{fgh}	1.51 ± 0.015^{bcde}	4.21 ± 0.014
A1B4	0.42 ± 0.002^{de}	0.95 ± 0.010^{defg}	1.39 ± 0.027^{efg}	3.11 ± 0.043
A2B1	0.38 ± 0.003^{ef}	0.98 ± 0.017^{cdef}	1.49 ± 0.017^{cde}	4.42 ± 0.001
A2B2	0.28 ± 0.002^{hij}	0.96 ± 0.001^{defg}	1.65 ± 0.025^{ab}	4.78 ± 0.028^{a}
A2B3	0.33 ± 0.001^{gh}	1.06 ± 0.012^{ab}	1.62 ± 0.016^{abc}	4.89 ± 0.004^{a}
A2B4	0.24 ± 0.000^{j}	0.96 ± 0.005^{defg}	1.64 ± 0.009^{ab}	5.01 ± 0.053^{a}
A3B1	0.29 ± 0.001^{h}	0.78 ± 0.013^{ij}	1.12 ± 0.012^{j}	2.46 ± 0.029
A3B2	0.47 ± 0.007^{b}	1.01 ± 0.007^{bcde}	1.43 ± 0.001^{defg}	3.17 ± 0.025
A3B3	0.44 ± 0.003^{cd}	0.89 ± 0.004^{gh}	1.35 ± 0.004^{fghi}	2.78 ± 0.002
A3B4	0.38 ± 0.002^{ef}	0.58 ± 0.007^{l}	1.22 ± 0.011^{ij}	3.96 ± 0.050
A4B1	0.29 ± 0.004^{hi}	0.91 ± 0.002^{fgh}	1.43 ± 0.027^{defg}	4.21 ± 0.044
A4B2	0.26 ± 0.003^{ij}	0.69 ± 0.008^{ijk}	1.27 ± 0.023^{hi}	3.93 ± 0.023
A4B3	0.27 ± 0.004^{ij}	0.61 ± 0.011^{k}	1.1 ± 0.014^{j}	4.01 ± 0.028
A4B4	0.24 ± 0.006^{j}	0.85 ± 0.012^{hi}	1.31 ± 0.005^{ghi}	4.11 ± 0.042
A5B1	0.37 ± 0.006^{fg}	0.93 ± 0.017^{fgh}	1.46 ± 0.001^{def}	3.38 ± 0.023
A5B2	0.40 ± 0.000^{ef}	1.01 ± 0.010^{bcd}	1.55 ± 0.027^{abcd}	4.22 ± 0.060
A5B3	0.45 ± 0.004^{b}	1.06 ± 0.003^{abc}	1.63 ± 0.008^{ab}	4.39 ± 0.076
A5B4	0.39 ± 0.007^{ef}	1.14 ± 0.016^{a}	1.57 ± 0.020^{abc}	4.38 ± 0.055
SE (d)	0.016	0.036	0.063	0.138
CD(P=0.05)	0.036	0.083	0.133	0.293

Table 9. Effect of spacing and biochar application on plant collar diameter at main treatments

Main Treatment mean	Initial (cm)	2 MAP (cm)	4 MAP (cm)	6 MAP (cm)
A_1 (1 m × 0.5 m)	0.447^{A}	0.995^{A}	1.43^{B}	3.52^{C}
A_2 (1 m × 1 m)	0.308^{C}	0.99^{A}	1.6^{A}	4.78^{A}
A_3 (1 m × 1.5 m)	0.395^{B}	0.815^{B}	1.28^{C}	3.09^{D}
A_4 (1.5 m × 1.5 m)	0.265^{D}	0.765^{B}	1.27^{C}	4.06^{B}
A_5 (2 m × 2 m)	0.403^{B}	1.035^{A}	1.55^{A}	4.69^{A}
SE (d)	0.013	0.022	0.03	0.072
CD (p=0.05)	0.031	0.052	0.07	0.169

Table 10. Effect of spacing and biochar application on plant collar diameter at sub treatments

Sub Treatment mean	Initial	2 MAP	4 MAP	6 MAP
B_1 (0 kg BC/plant)	0.36^{B}	0.93^{AB}	1.38^{B}	3.56^{B}
B_2 (1 kg BC/plant)	0.39^{A}	0.95^{A}	1.47^{A}	3.90^{A}
B_3 (2 kg BC/plant)	0.38^{A}	0.91^{BC}	1.44^{A}	4.06^{A}
B_4 (3 kg BC/plant)	0.33^{C}	0.89^{C}	1.43^{A}	4.11^{A}
SE (d)	0.007	0.016	0.029	0.061
CD (p=0.05)	0.015	0.033	0.059	0.124

Table 11. Effect of spacing and biochar application on number of branches

Treatment combinations	Initial	2 MAP	4 MAP	6 MAP
A1B1	8 ± 0.069	17 ± 0.56[a]	24 ± 0.45	31 ± 0.45
A1B2	11 ± 0.101	19 ± 0.68[a]	27 ± 0.44	38 ± 0.89
A1B3	9 ± 0.151	17 ± 0.90[a]	30 ± 1.79[a]	43 ± 1.24[a]
A1B4	5 ± 0.031	11 ± 0.56	19 ± 0.68	30 ± 1.18
A2B1	7 ± 0.114	13 ± 1.01	22 ± 1.12	32 ± 1.18
A2B2	10 ± 0.120	17 ± 0.72[a]	30 ± 1.57[a]	40 ± 1.69[a]
A2B3	11 ± 0.013	17 ± 0.68[a]	31 ± 0.90[a]	42 ± 1.27[a]
A2B4	5 ± 0.063	12 ± 0.85	24 ± 1.06	32 ± 1.23
A3B1	5 ± 0.006	10 ± 0.85	20 ± 1.27	29 ± 0.81
A3B2	6 ± 0.114	11 ± 0.79	23 ± 0.67	32 ± 0.34
A3B3	7 ± 0.074	11 ± 0.56	20 ± 0.68	30 ± 1.02
A3B4	5 ± 0.090	10 ± 0.68	18 ± 1.13	27 ± 1.24
A4B1	6 ± 0.012	12 ± 0.68	23 ± 1.90	30 ± 2.08
A4B2	6 ± 0.019	11 ± 0.45	21 ± 0.89	32 ± 0.90
A4B3	4 ± 0.061	10 ± 0.34	19 ± 0.56	30 ± 0.22
A4B4	6 ± 0.079	12 ± 0.47	22 ± 0.85	28 ± 1.86
A5B1	5 ± 0.045	11 ± 0.34	21 ± 0.67	32 ± 1.01
A5B2	6 ± 0.054	14 ± 0.45	29 ± 0.56	40 ± 1.15[a]
A5B3	7 ± 0.010	13 ± 0.56	22 ± 1.16	32 ± 0.93
A5B4	9 ± 0.141	16 ± 0.56	29 ± 1.01[a]	39 ± 1.00
SE (d) CD(P=0.05)	NS	3.956	3.188	3.655

Table 13. Effect of spacing and biochar application on number of branches at sub treatments

Sub Treatment mean	Initial (cm)	2 MAP (cm)	4 MAP (cm)	6 MAP (cm)
B_1 (0 kg BC/plant)	8	13	26	35
B_2 (1 kg BC/plant)	5	14	20	30
B_3 (2 kg BC/plant)	5	14	21	31
B_4 (3 kg BC/plant)	6	12	27	37
SE (d) CD (p=0.05)	NS	NS	NS	NS

Table 12. Effect of spacing and biochar application on number of branches at main treatments

Main Treatment mean	Initial (cm)	2 MAP (cm)	4 MAP (cm)	6 MAP (cm)
A_1 (1 m × 0.5 m)	8	16	25	35
A_2 (1 m × 1 m)	8	15	27	37*
A_3 (1 m × 1.5 m)	6	10	20	30
A_4 (1.5 m × 1.5 m)	6	11	21	32
A_5 (2 m × 2 m)	7	14	25	38*
SE (d) CD (p=0.05)	NS	NS	NS	NS

Table 14. Effect of spacing and biochar application on sturdiness quotient

Treatment combinations	Initial	2 MAP	4 MAP	6 MAP
A1B1	147.8 ± 2.582	108.2 ± 0.215	138.2 ± 0.870	96.9 ± 0.760
A1B2	133.1 ± 1.072	108.7 ± 1.560	133.7 ± 1.964	90.6 ± 0.703
A1B3	160.5 ± 1.965	115.0 ± 2.273	125.2 ± 2.440	80.7 ± 0.069
A1B4	151.9 ± 2.207	109.5 ± 0.258	126.7 ± 1.976	95.8 ± 0.586
A2B1	159.5 ± 3.145	106.5 ± 0.074	125.5 ± 1.704	76.1 ± 1.170
A2B2	182.9 ± 0.214	102.5 ± 0.476	118.8 ± 1.446	83.1 ± 0.624
A2B3	170.9 ± 3.312	94.5 ± 1.427	122.8 ± 2.383	82.1 ± 1.082
A2B4	208.3 ± 1.886	98.3 ± 0.322	120.1 ± 2.273	83.2 ± 1.420
A3B1	183.4 ± 0.567	113.6 ± 1.401	142.7 ± 2.265	112.8 ± 1.360
A3B2	134.9 ± 1.593	101.0 ± 1.838	122.4 ± 0.104	96.6 ± 1.323
A3B3	138.6 ± 1.774	109.4 ± 1.376	122.9 ± 1.373	104.2 ± 2.086
A3B4	130.5 ± 2.218	141.0 ± 0.026	129.8 ± 1.299	83.8 ± 0.273
A4B1	192.4 ± 2.689	106.8 ± 0.812	129.9 ± 0.985	85.3 ± 0.054
A4B2	202.3 ± 1.327	128.1 ± 1.403	132.1 ± 0.320	83.3 ± 1.052
A4B3	187.4 ± 2.773	136.7 ± 2.495	145.5 ± 2.875	79.6 ± 0.004
A4B4	239.2 ± 2.016	109.6 ± 1.004	130.3 ± 0.432	77.4 ± 0.563
A5B1	164.3 ± 2.702	104.9 ± 2.084	117.3 ± 1.716	90.7 ± 1.053
A5B2	145.0 ± 2.874	99.8 ± 0.913	120.9 ± 1.892	89.6 ± 0.675
A5B3	141.8 ± 2.292	96.2 ± 0.824	117.0 ± 0.974	86.9 ± 1.620
A5B4	146.2 ± 2.192	97.9 ± 0.541	120.1 ± 0.055	85.1 ± 0.908
SE (d) CD(P=0.05)	NS	3.956	3.188	3.655

Table 15. Effect of spacing and biochar application on sturdiness quotient at main treatments

Main Treatment mean	Initial (cm)	2 MAP (cm)	4 MAP (cm)	6 MAP (cm)
A_1 (1 m × 0.5 m)	148.3	110.3	130.9	130.9
A_2 (1 m × 1 m)	180.4	100.5	121.8	121.8
A_3 (1 m × 1.5 m)	146.9	116.3	129.5	129.5
A_4 (1.5 m × 1.5 m)	205.3	120.3	134.4	134.4
A_5 (2 m × 2 m)	149.3	99.7	118.8	118.8
SE (d) CD (p=0.05)	NS			

Table 16. Effect of spacing and biochar application on sturdiness quotient at sub treatments

Sub Treatment mean	Initial (cm)	2 MAP (cm)	4 MAP (cm)	6 MAP (cm)
B_1 (0 kg BC/plant)	65.9	328.925	186.75	317.5
B_2 (1 kg BC/plant)	54.55	298.075	194.75	388
B_3 (2 kg BC/plant)	56.8	273.625	164.795	301.258
B_4 (3 kg BC/plant)	54.1	271.675	171.06	330.892
SE (d) CD (p=0.05)	NS	1.826 4.277	4.591 10.75	7.505 17.576

Table 17. Effect of spacing and biochar application on volume index (cm^3)

Treatment combinations	Initial	2 MAP	4 MAP	6 MAP
A1B1	11.3 ± 0.201	94.6 ± 0.111	300.6 ± 5.000	4593.6 ± 16.787
A1B2	14.7 ± 0.133	109.9 ± 0.116	330.3 ± 5.840	3805.6 ± 9.677
A1B3	7.5 ± 0.002	73.2 ± 0.437	368.7 ± 1.693	5183.7 ± 102.10
A1B4	8.9 ± 0.175	76.1 ± 0.856	255.7 ± 0.626	3591.6 ±10.641
A2B1	6.9 ± 0.075	80.9 ± 0.213	375.4 ± 3.062	5589.5 ± 111.94
A2B2	3.2 ± 0.010	74.3 ± 1.471	487.5 ± 9.704	8291.3 ± 91.467
A2B3	4.8 ± 0.077	91.8 ± 1.319	448.3 ± 2.120	7610.3 ± 72.843
A2B4	2.3 ± 0.037	72.5 ± 1.400	458.3 ± 8.416	7510.9 ± 97.041
A3B1	3.5 ± 0.035	44.8 ± 0.332	183.4 ± 2.964	3516.4 ± 7.423
A3B2	11.0 ± 0.006	83.9 ± 0.056	310.6 ± 5.426	3840.2 ± 11.226
A3B3	9.3 ± 0.003	63.1 ± 0.322	277.6 ± 2.303	3717.8 ± 55.550
A3B4	1.3 ± 0.019	23.0 ± 0.055	180.2 ± 2.790	4619.0 ± 45.635
A4B1	3.7 ± 0.005	65.7 ± 0.253	342.9 ± 6.439	5301.9 ± 63.576
A4B2	2.8 ± 0.002	36.2 ± 1.595	341.2 ± 0.570	4406.8 ± 76.919
A4B3	1.9 ± 0.005	27.8 ± 1.417	191.3 ± 3.366	4897.0 ± 15.805
A4B4	6.5 ± 0.005	55.1 ± 0.098	259.2 ± 0.007	4971.9 ± 95.546
A5B1	6.5 ± 0.036	70.6 ± 1.347	342.7 ± 2.882	4171.7 ± 8.738
A5B2	7.3 ± 0.041	85.4 ± 0.266	411.7 ± 3.693	6797.0 ± 2.478
A5B3	10.2 ± 0.077	95.0 ± 1.454	461.9 ± 4.108	6476.2 ± 124.95
A5B4	6.81 ± 0.130	118.49 ± 0.716	422.81 ± 8.463	6287.58 ± 92.479
SE (d) CD(P=0.05)	NS	3.106 6.457	15.075 32.616	250.094 526.348

Table 18. Effect of spacing and biochar application on volume index at main treatments

Main Treatment mean	Initial (cm)	2 MAP (cm)	4 MAP (cm)	6 MAP (cm)
A_1 (1 m × 0.5 m)	10.6	86.0	313.8	4293.6
A_2 (1 m × 1 m)	4.3	79.9	442.4	7250.5
A_3 (1 m × 1.5 m)	6.3	56.1	238.0	3923.4
A_4 (1.5 m × 1.5 m)	3.7	48.7	283.6	4894.4
A_5 (2 m × 2 m)	7.7	90.6	409.8	5933.1
SE (d) CD (p=0.05)	NS	0.941 2.203	10.319 24.166	106.43 249.23

Table 19. Effect of spacing and biochar application on volume index at sub treatments

Sub Treatment mean	Initial (cm)	2 MAP (cm)	4 MAP (cm)	6 MAP (cm)
B_1 (0 kg BC/plant)	6.4	72.0	309.0	4634.6
B_2 (1 kg BC/plant)	5.2	73.9	376.3	5428.2
B_3 (2 kg BC/plant)	4.6	72.2	349.6	5577.0
B_4 (3 kg BC/plant)	5.1	70.9	315.2	5396.2
SE (d) CD (p=0.05)	NS NS	NS NS	6.742 13.836	116.871 239.846

Biomass

Woody biomass at 6 MAP varied significantly across treatments. The maximum biomass (5886.8 g) was observed in A2B2 (1 m × 1 m spacing, 1 kg biochar/plant) and the minimum (2496.6 g) was recorded in A3B1 (1 m × 1.5 m spacing, no biochar). Among spacing treatments, A2 (1 m × 1 m) produced the highest biomass (5147.9 g), while A3 (1 m × 1.5 m) yielded the lowest (2785.6 g). At the biochar level, B3 (2 kg biochar/plant) resulted in the maximum biomass (3959.7 g), on par with B2 (1 kg biochar/plant), while the lowest biomass (3290.6 g) was recorded in B1 (no biochar). Differences were statistically significant at the 5 % level ($p < 0.05$) as shown in Table 20.

These results highlight the significant influence of spacing and biochar levels on the survival and growth of Casuarina hybrid clones, with narrower spacing and moderate biochar doses yielding optimal results. These findings highlight that moderate spacing (1 m × 1 m) combined with 1 - 2 kg biochar per plant optimizes both volume index and biomass production in Casuarina hybrid plantations.

Discussion

This study demonstrates the potential of optimized silvicultural practices, such as spacing and biochar application on the growth parameters of Casuarina hybrid clone (A-01) highlights the synergistic effects of these factors in optimizing productivity, particularly in arid and semi-arid regions. The study revealed significant variation in height, basal diameter and volume index under different spacing and biochar treatments, highlighting the importance of optimal planting densities and species selection for maximizing forest productivity (8, 9). Specifically, the tallest plants (416.8 cm) were observed in the A2B4 treatment (1 m × 1 m spacing, 3 kg biochar/plant), while the shortest (277.4 cm) were noted in A3B1 (1 m × 1.5 m spacing, 0 kg biochar/plant) (Fig. 4). These results align with earlier findings that demonstrated biochar's capacity to enhance biomass production by improving soil-plant interactions (10, 11).

Furthermore, biochar applications significantly enhanced collar diameter, with the highest diameter (5.01 cm) recorded in A2B4 and the lowest (2.46 cm) in A3B1, supporting the findings of (12) and (13) who observed improved growth metrics due to biochar-induced soil fertility improvements (Fig. 5). The maximum volume and biomass recorded in A2B2 (8291.3 cm^3 and 5886.8 g, respectively) further validate biochar's role in fostering sustainable growth, aligning with previous studies which highlighted higher productivity in denser plantations (Fig. 6, 7) (14, 15).

Interestingly, while high-density plantations typically yield uniform size distributions (16), the current findings suggest variability in individual tree performance, possibly due to interactive effects of biochar and spacing. This observation differs from earlier reports of reduced growth metrics at higher planting densities but supports the finding that wider spacings can enhance height growth (17). The interactive effects of biochar and fertilizers were evident in this study, where combined applications enhanced both biomass and soil health, albeit differing from the isolated biochar treatments in prior studies (18, 19). The results underscore the potential of biochar amendments combined with optimal spacing to maximize growth and biomass production in Casuarina hybrid clone (A-01) plantations. This aligns with previous studies which demonstrated significant yield improvements with biochar, especially when integrated with fertilizers. The findings provide a robust framework for leveraging biochar and spacing strategies in agroforestry systems to enhance resource efficiency and sustainability (20-22).

Overall, the findings reinforce the importance of tailored management practices, including moderate planting density and biochar application, in promoting sustainable biomass production and aligning with global efforts toward renewable energy solutions.

Conclusion

The study on the influence of variable spacings and biochar doses on the growth and biomass production of Casuarina hybrid clone (A-01) has yielded critical insights for optimizing energy plantations in resource-limited regions. Among the five spacing treatments and four biochar doses tested, specific combinations demonstrated significant effects on survival rates, growth metrics and overall productivity. The highest survival percentage (100 %) was recorded in combinations like A1B3 (1 m × 0.5 m spacing, 2 kg biochar/plant), emphasizing the synergistic benefits of moderate biochar application in closer spacings. Similarly, the maximum plant height (416.8 cm), collar diameter (5.01 cm) and volume index (8291.3 cm^3) were observed in treatments like A2B4 (1 m × 1 m spacing, 3 kg biochar/plant), underscoring the role of optimal spacing and higher biochar doses in promoting growth.

Table 20. Effect of spacing and biochar application on biomass (kg $plant^{-1}$)

Spacing level (m*m) \ Biochar doses (kg/plant)	Biomass (kg $plant^{-1}$)					
	B1 (0)	B2 (1)	B3 (2)	B4 (3)	Mean	Main effects (spacing)
A_1 (1 m × 0.5 m)	3261.5 ± 30.91	2702.0 ± 43.79	3680.4 ± 28.25	2550.1 ± 27.81	3048.5	3048.5
A_2 (1 m × 1 m)	3968.6 ± 68.49	5886.8 ± 54.40	5403.3 ± 98.21	5332.7 ± 48.99	5147.9	5147.9
A_3 (1 m × 1.5 m)	2496.6 ± 6.73	2726.5 ± 46.90	2639.7 ± 4.04	3279.5 ± 2.56	2785.6	2785.6
A_4 (1.5 m × 1.5 m)	3764.4 ± 68.61	3128.8 ± 43.91	3476.9 ± 49.42	3530.0 ± 69.88	3475.0	3475.0
A_5 (2 m × 2 m)	2961.9 ± 48.35	4825.9 ± 31.68	4598.1 ± 2.42	4464.2 ± 89.41	4212.5	4212.5
Mean	3290.6	3854.0	3959.7	3831.3	3733.9	
Main effects (biochar doses)	3290.6	3854.0	3959.7	3831.3		
	A	**B**	**A at B**		**B at A**	
SE(d)	100.762	81.497	182.234		187.243	
CD(p=0.05)	235.961	167.245	389.256		399.955	

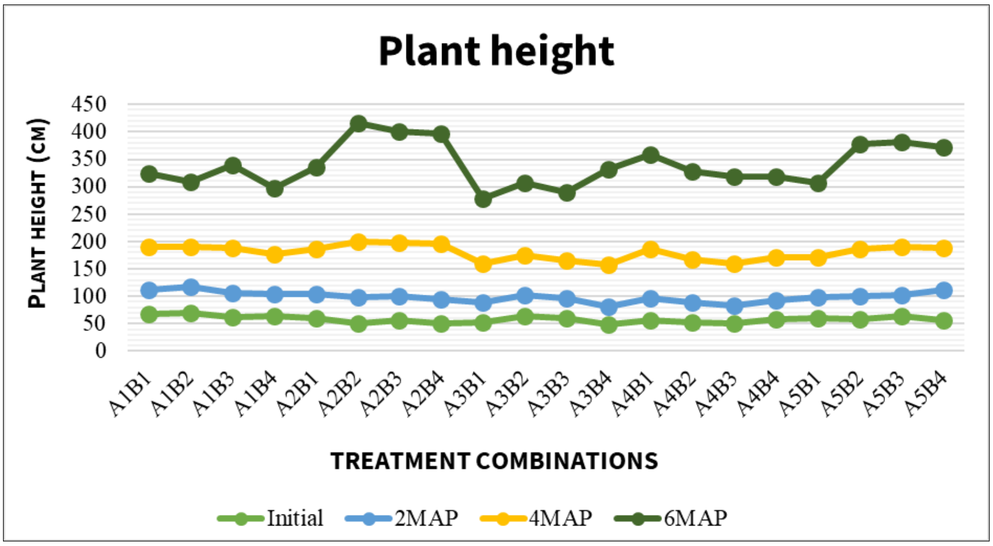

Fig. 4. Effect of spacing and biochar application on plant height (cm).

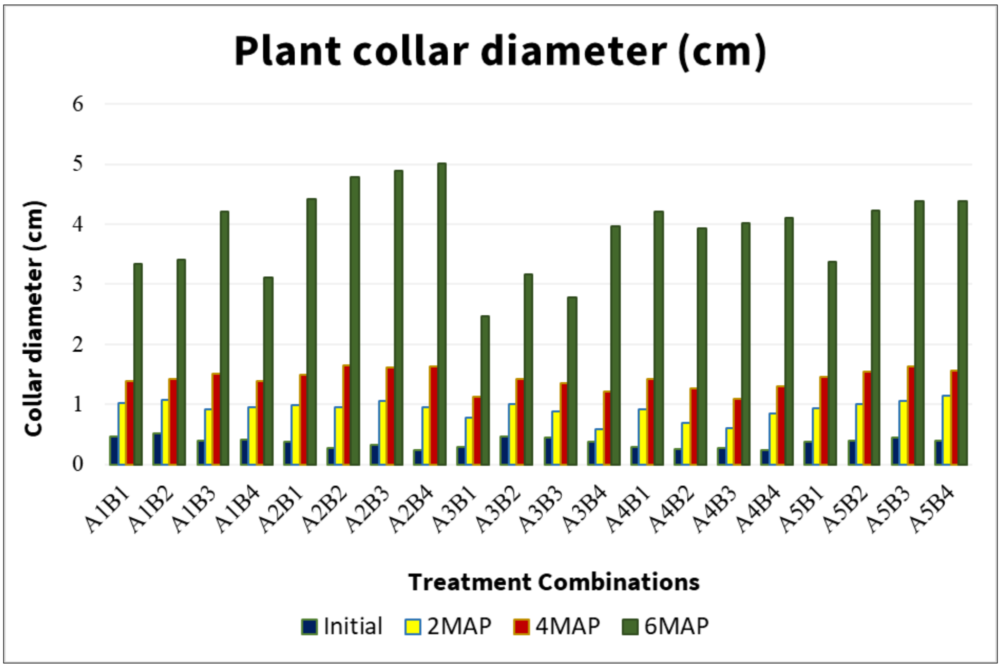

Fig. 5. Effect of spacing and biochar application on plant collar diameter.

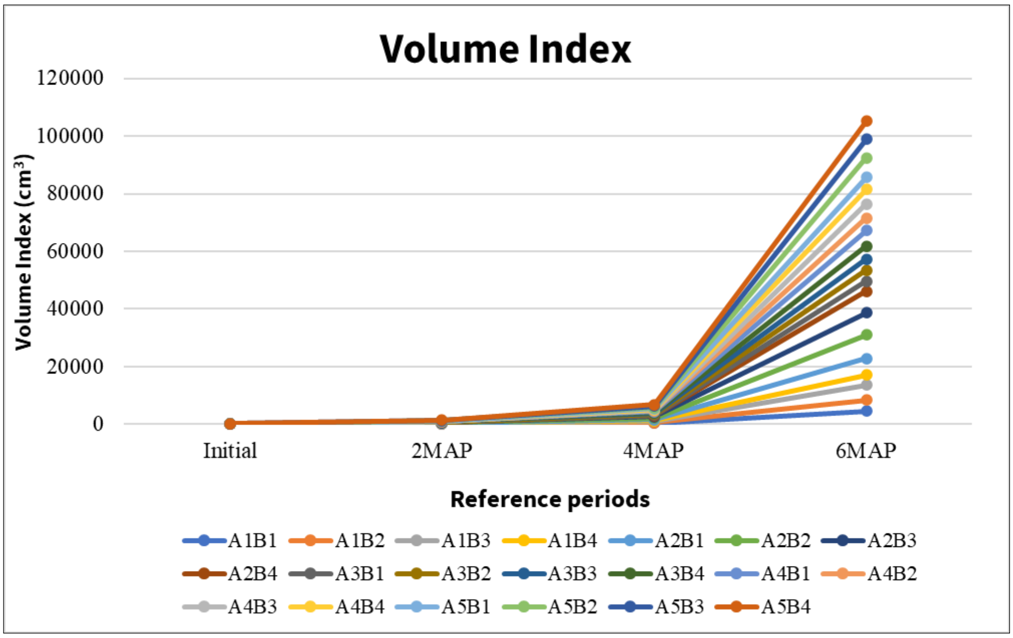

Fig. 6. Effect of spacing and biochar application on volume index.

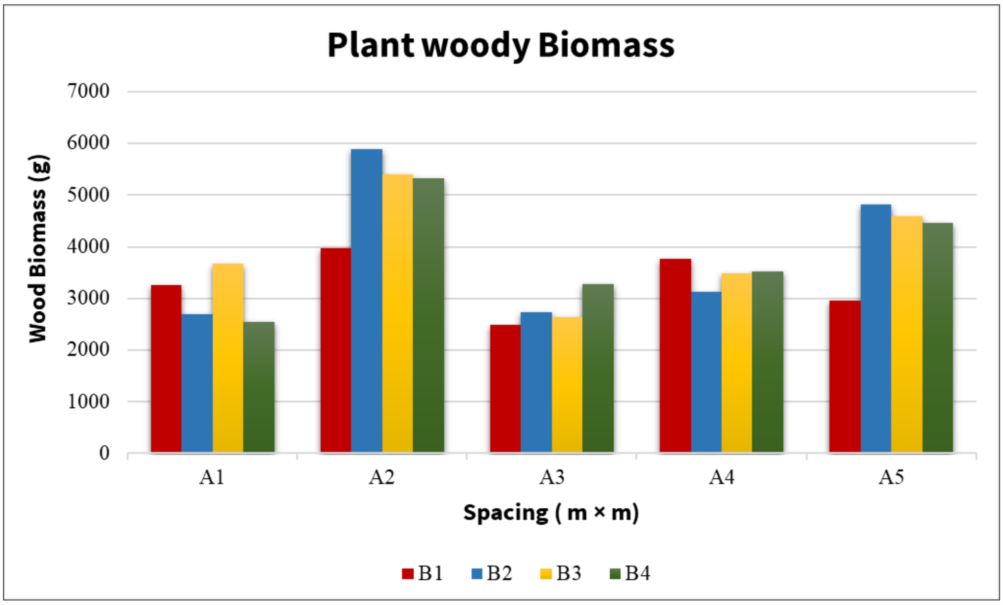

Fig. 7. Effect of spacing and biochar application on wood biomass.

Biochar application significantly influenced growth characteristics, with B3 (2 kg biochar/plant) consistently enhancing survival, volume and biomass across spacing's. Treatments like A2B2 (1 m × 1 m spacing, 1 kg biochar/plant) also recorded notable results for volume index and biomass, reinforcing the importance of medium biochar application rates in balancing resource use and productivity. Wider spacings like A5 (2 m × 2 m) supported a higher number of branches, while closer spacings like A1 (1 m × 0.5 m) achieved better survival rates, reflecting the trade-offs inherent in spacing decisions for energy plantations.

The findings also highlight the complexity of interactions between spacing and biochar, with sturdiness quotient and biomass showing varied responses depending on treatment combinations. For instance, the highest sturdiness quotient (112.8) in A3B1 (1 m × 1.5 m spacing, no biochar) reflects specific advantages of medium spacing under limited resource input conditions. The observed trends align with previous studies on biochar's role in improving soil properties and plant growth, demonstrating its potential as a sustainable amendment in agroforestry systems.

In conclusion, the research establishes the combination of 1 m × 1 m spacing and 2 - 3 kg biochar per plant as optimal for maximizing growth, survival and biomass production in Casuarina hybrid clone (A-01) plantations. These results provide valuable recommendations for designing energy plantations that balance high productivity with resource efficiency, paving the way for sustainable forestry practices in arid and semi-arid regions.

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Authors' contributions

PK, RP, KTP and SR contributed to the conceptualization of the study and the design of the research work. M. Kiruba developed the methodology while BS was responsible for supervision and validation. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare no conflict of interest.

Ethical issues: None

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