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Energy Characteristics of Clonal Teak Logging Waste from Paliyan-Gunungkidul, Indonesia

Karakteristik Energi Limbah Tebangan Jati Klonal dari Paliyan-Gunungkidul

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ABSTRACT

Breeding teak with a clonal system was a common practice to enhance productivity and reduce rotation. A private company in Paliyan Sub-District, Gunungkidul Regency, Indonesia, developed *Jati Unggul Nusantara (JUN)* through vegetative propagation, particularly cloning, using cuttings. JUN had gained widespread popularity as a replacement for conventional teak varieties for commercial purposes. The utilization of JUN commercial timber left various non-commercial biomass forms, such as leaves, branches, and twigs. This research aimed to assess JUN logging waste biomass's energy potential and characteristics across different tree-age stands. This research used non-commercial biomass from six- and eight-year-old trees, including branches, twigs, leaves, stumps, and unmerchantable top stems. The results showed that the average dry weight of JUN logging waste from six- and eight-year-old trees was 31.5 and 53.5 kg/tree, while the calorific value ranged from 4516.4–5177.7 cal/g. This waste had good characteristics as an energy material, specifically from the part of unmerchantable top stems with a high fuelwood value index of 6579.6.

KATA KUNCI
Jati, umur, limbah tebangan, energi, indeks kayu bakar

INTISARI

Pembiakan dengan system klonal telah banyak dilakukan pada jati untuk meningkatkan produktivitasnya maupun memperpendek daurnya. Jati Unggul Nusantara (JUN) adalah salah satu tanaman jati yang berasal dari pembiakan (propagasi) vegetatif (kloning) dengan stek pucuk dari jenis unggul jati yang dikembangkan oleh salah satu perusahaan swasta di wilayah Kecamatan Paliyan, Kabupaten Gunungkidul. Saat ini JUN mulai ditanam secara luas untuk menggantikan jati konvensional. Penebangan memanfaatkan batang yang bernilai komersial dan meninggalkan berbagai jenis biomassa non komersial seperti daun, cabang, dan ranting. Penelitian ini bertujuan untuk menilai potensi dan karakteristik energi biomassa limbah tebangan JUN dari berbagai umur tegakan. Bahan yang digunakan dalam penelitian ini adalah biomassa non komersial (cabang, ranting, daun, tunggak sisa tebangan, maupun batang di atas bebas cabang) dari tanaman JUN umur 6 dan 8 tahun. Hasil penelitian menunjukkan bahwa rata-rata berat kering limbah tebangan JUN umur 6 dan 8 tahun adalah 31,5 dan 53,5 kg per pohon. Nilai kalor berkisar antara 4516,4–5177,7 cal/g. Limbah ini memiliki karakteristik yang baik sebagai bahan energi, khususnya dari bagian batang di atas bebas cabang dengan nilai indeks kayu bakar yang tinggi yaitu 6579,6.

Introduction

Teak is a high-quality and economically valuable type of wood widely recognized and cultivated by the community for a long time. Furthermore, it has become a primary plant managed by Perhutani. The high demand for teak has led several private companies to develop superior species characterized by favorable phenotypes and rapid growth, leading to a shorter rotation. PT. Surya Silva Mataram in Gunungkidul, Yogyakarta, Indonesia, has developed a superior species called Jati Unggul Nusantara (JUN).

JUN is a teak plant from vegetative propagation (cloning) using cuttings of a superior species developed by a private company in Paliyan Sub-district, Gunungkidul Regency. JUN is estimated to grow relatively fast, allowing for harvest at five years, yielding approximately 0.2 m3/tree in logs (Anonymous 2011). JUN, planted in Paliyan, Gunungkidul, has reached six and eight years old. Unlike conventional teak managed by Perhutani, which has a 40-year rotation, JUN has a shorter rotation. The teak harvesting process produces commercial assortments (logs) and generates logging residues classified as fuelwood. The biomass categorized as fuelwood includes branches, twigs, leaves, bark, and roots (Tabata 2018). So far, the company has donated this logging waste biomass to the local community as part of the Company's care program, and they can use it as fuelwood.

In developing countries such as Indonesia, fuelwood has become a widely used commodity for household energy sources (Anonymous 2020). On average, biomass accounts for up to 35% of the total energy requirements, serving as household and industrial fuel. Its application as fuel provides significant benefits to the community as long as considering the environmental impact. The communities surrounding the forest areas experience no energy crisis like their counterparts in urban areas because they rely on fuelwood as a household energy source.

Numerous research examined the quality of teak wood (Hidayati et al. 2016; Lukmandaru et al. 2016; Zulkahfi et al. 2020; Putro et al. 2020), durability (Lukmandaru et al. 2018; Marta et al. 2021), calculation of biomass potential in teak trees (Kenzo et al. 2020; Wirabuana et al. 2022), use of industrial waste from teak wood production for energy (Iskandar et al. 2020; Wibowo et al. 2022), and teak tree pruning (Prasaningtyas & Sulistyo 2014; Arevalo & Marti 2020). Previous research suggested that industrial waste and pruning residues from teak trees exhibit promising potential as energy sources. However, there needs to be more information about the potential and characteristics of JUN logging waste, particularly concerning its fast growth and shorter rotation. Therefore, this research aimed to calculate the potential and analyze the quality of JUN logging waste as fuelwood.

Materials and Methods

Materials

This research used above-ground biomass components, including commercial stems, stumps (T), unmerchantable top stems (BA), branches (C), twigs (R), and leaves (D) from six and eight-year-old JUN plants obtained from JUN teak plantation owned by PT. Surya Silva Mataram in Paliyan Sub-district, Gunungkidul Regency. For each age group, three trees were felled with an average diameter at breast height (DBH) of 15.3 cm and 14.7 cm for six and eight-year-old trees, respectively. The weight of each part of biomass was measured, except for stumps. Stump only became samples for the energy characteristics assessment. Commercial stems were weighted, with no energy characteristics assessment.

Methods

Moisture Content

Samples were weighed at two g to establish the initial weight, then placed in an oven at a temperature of 103±2°C for approximately two hours. The dried samples were cooled in a desiccator and reweighed. The process continued until it attained a constant weight. The calculation of moisture content used the following formula.

$$MC\ (\%) = \frac{\text{initial weight} - \text{final weight}}{\text{initial weight}}\ x\ 100\%$$

Oven-dried Density

Samples were weighed up to two g and dried in an oven at a temperature of 103±2°C until they reached a constant weight. Then, the sample were immediately immersed in paraffin and measuring the volume. The calculation of oven-dried sample density used the following formula.

$$\text{OdD} = \frac{\text{oven} - \text{dried weight}}{\text{oven} - \text{dried volume}}$$

Wood Chemical Analysis

Chemical test samples were finely ground and sieved to pass through a 40-mesh while retained on a 60-mesh sieve. A two g powder sample was tested for ethanol-toluene soluble extractive content using the Soxhlet method following TAPPI T204 test standards. By hydrolyzing the extractive-free powder sample with 72% sulfuric acid, klason lignin content was determined (Irawati et al. 2012).

Proximate Wood Analysis

Ash

Approximately two g (±0.1 g) powder was placed in a weight-known porcelain crucible and heated in a furnace at 600°C for four hours. The furnace lid was then opened for about one minute to ensure complete combustion and turn the powder into ash. The sample was cooled in a desiccator and weighed until a constant weight. The measurement of ash content used three replications.

Volatile

Approximately two g (±0.1 g) of powder was placed in a weight-known porcelain crucible and heated in an oven at 900°C for 15 minutes. The sample was then cooled and transferred to a desiccator before being weighed. The measurement of volatile content used three replications.

Fixed carbon

Fixed carbon content refers to the fraction of carbon in charcoal other than ash, volatile matter, and water. The calculation of fixed carbon followed the ASTM D-3172 standard.

Wood Calorific Value

A calorific value test used an oxygen bomb calorimeter and followed ASTM 2015 methods. Approximately one gram of the sample, conditioned in an oven at 45°C, was placed in a cup and combusted within the cylindrical bomb, and the increased temperature after the combustion was measured. The combustion residue was cleaned with distilled water, collected in a 50 ml beaker, and titrated with a Na_2CO_3 solution.

Calculation of Fuelwood Value Index

The Fuelwood Value Indeks (FVI) became a standard indicator for biomass suitability as fuelwood (Ramos et al. 2008; Chettri & Sharma 2009). The calculation of FVI used the following formula. In this research, the FVI measurement was in oven-dry conditions.

$$\text{FVI} = \frac{\text{calorific value x density}}{\text{ash content x moisture content}}$$

Data Analysis

This research used a factorial design to investigate the relationship between age, biomass types, and biomass characteristics.

Results and Discussion

Biomass Composition

Table 1 presented data on the total weight and moisture content of six and eight-year-old JUN biomass, including commercial stems, unmerchantable top stems (BA), branches (C), twigs (R), and leaves (D). The average height, DBH, and fresh weight of six and eight-year-old JUN trees were 16.5 m and 15.3 cm, 15.7 m and 14.7 cm, and 162.1 and 183.3 tons, respectively. In this research, the percentage of branches and twigs was higher than in the previous research on the Jati Plus Perhutani samples (Wirabuana 2022). Employing the allometric equation of Kenzo et al. (2020), the weight of JUN dried branches was slightly higher, indicating that JUN produced more biomass than other teaks. Stems constituted the most considerable portion of six and eight-year-old JUN biomass at 75.7% and 79.2%, followed by branches, twigs, and leaves. These results

Table 1. Fresh weight and green moisture content of JUN biomass

Ages (years)	Biomass Types	Fresh weight (kg)	Green moisture content (%)	Dry weight (kg)	Percentage of total (%)
6	Commercial stems	113.5 ± 16.8	46.5 ± 2.4	60.9 ± 10.8	65.5
	Unmerchantable top stems (BA)	17.0 ± 3.6	43.6 ± 3.5	9.5 ± 1.4	10.2
	Branches (C)	19.0 ± 6.0	30.4 ± 9.1	13.3 ± 4.6	14.3
	Twigs ®	9.5 ± 4.3	27.6 ± 17.9	6.6 ± 3.2	7.1
	Leaves (D)	3.1 ± 2.7	20.5 ± 5.9	2.6 ± 2.4	2.8
	TOTAL	162.1 ± 29.9		93.0 ± 19.2	100
8	Commercial stems	99.7 ± 27.6	36.4 ± 0.8	63.4 ± 17.1	54.2
	Unmerchantable top stems (BA)	44.6 ± 9.8	34.3 ± 6.0	29.2 ± 6.0	25.0
	Branches (C)	28.0 ± 8.6	34.3 ± 6.1	18.0 ± 3.8	15.4
	Twigs (`R)	9.8 ± 6.3	39.3 ± 20.3	5.5 ± 2.8	4.7
	Leaves (D)	1.3 ± 2.2	37.5	0.8 ± 1.4	0.7
	TOTAL	183.3 ± 53.4		116.9 ± 28.7	100

Table 2. Analysis of variance on JUN biomass from two different ages (six and eight years old)

Parameter	Source of variation	Sum of Squares	Degree of Freedom	Mean square	F	Sig.
Fresh weight of commercial stems	Age	285.38	1.00	285.38	0.55	0.50^{ns}
	Error	2092.17	4.00	523.04		
	Total	2377.56	5.00			
Fresh weight of BA	Age	1137.68	1.00	1137.68	20.82	0.01**
	Error	218.61	4.00	54.65		
	Total	1356.29	5.00			
Fresh weight of C	Age	121.32	1.00	121.32	2.19	0.21^{ns}
	Error	221.52	4.00	55.38		
	Total	342.84	5.00			
Fresh weight of R	Age	0.15	1.00	0.15	0.01	0.95^{ns}
	Error	115.24	4.00	28.81		
	Total	115.40	5.00			
Fresh weight of D	Age	5.01	1.00	5.01	0.84	0.41^{ns}
	Error	23.94	4.00	5.98		
	Total	28.94	5.00			
The green moisture content of commercial stems	Age	151.11	1.00	151.11	48.71	0.00**
	Error	12.41	4.00	3.10		
	Total	163.52	5.00			
The green moisture content of BA	Age	131.38	1.00	131.38	5.39	0.08^{ns}
	Error	97.44	4.00	24.36		
	Total	228.82	5.00			
The green moisture content of C	Age	23.02	1.00	23.02	0.38	0.57^{ns}
	Error	239.31	4.00	59.83		
	Total	262.33	5.00			
The green moisture content of R	Age	206.00	1.00	206.00	0.56	0.50^{ns}
	Error	1465.32	4.00	366.33		
	Total	1671.32	5.00			
Dry weight of commercial stems	Age	8.70	1.00	8.70	0.04	0.85^{ns}
	Error	820.25	4.00	205.06		
	Total	828.95	5.00			
The dry weight of BA	Age	581.28	1.00	581.28	30.53	0.01**
	Error	76.15	4.00	19.04		
	Total	657.44	5.00			
The dry weight of C	Age	416.32	1.00	416.32	27.77	0.01**
	Error	59.97	4.00	14.99		
	Total	476.29	5.00			
The dry weight of R	Age	1.87	1.00	1.87	0.21	0.67^{ns}
	Error	36.44	4.00	9.11		
	Total	38.30	5.00			
The dry weight of D	Age	4.69	1.00	4.69	1.25	0.33^{ns}
	Error	15.02	4.00	3.76		
	Total	19.71	5.00			

Description: (**) = highly significant, α = 0.01; (ns) = non-significant

Table 3. The average value of ethanol-toluene extractive content, Klason lignin content, density, proximate, calorific value, and fuelwood value index of six and eight-year-old JUN biomass.

Parameter	Six years old**					Eight years old***				
	T	BA*	C*	R*	D*	T	BA*	C*	R*	D*
Oven-dried Density (g/cm^3)	0.63 ± 0.05	0.68 ± 0.09	0.64 ± 0.10	0.53 ± 0.12	0.78 ± 0.16	0.58 ± 0.05	0.63 ± 0.06	0.68 ± 0.08	0.55 ± 0.05	0.83 ± 0.00
Extractive content (%)	3.05 ± 0.47	4.29 ± 0.76	4.67 ± 0.27	6.33 ± 1.40	-	6.13 ± 0.81	7.67 ± 3.26	8.87 ± 1.99	10.9 ± 2.12	-
Lignin content (%)	26.9 ± 0.99	23.4 ± 1.31	20.7 ± 1.14	18.1 ± 0.31	-	28.0 ± 3.27	24.0 ± 2.42	26.8 ± 1.91	21.4 ± 1.83	-
Ash content (%)	0.63 ± 0.16	0.90 ± 0.41	2.76 ± 0.56	5.33 ± 0.63	10.0 ± 2.96	4.47 ± 1.52	0.45 ± 0.05	1.91 ± 1.18	3.87 ± 0.44	6.26 ± 0.00
Volatile content (%)	81.6 ± 1.18	82.4 ± 1.17	87.9 ± 4.13	84.8 ± 2.25	77.0 ± 1.55	76.1 ± 3.38	80.0 ± 1.16	79.4 ± 1.96	77.2 ± 0.47	70.8 ± 0.00
Fixed carbon content (%)	17.8 ± 1.12	16.7 ± 0.90	9.30 ± 4.45	9.80 ± 2.78	13.0 ± 2.05	19.4 ± 1.88	19.5 ± 1.19	18.7 ± 1.27	18.9 ± 0.51	22.9 ± 0.00
Calorific value (cal/g)	4679.9 ± 417.2	4516.4 ± 441.5	4839.7 ± 107.1	5177.7 ± 329.2	4923.0 ± 1504.4	4900.6 ± 211.0	4677.6 ± 166.3	4702.0 ± 168.0	4653.6 ± 89.8	-
Fuelwood value index	4991.6 ± 1846.0	3712.8 ± 998.6	1164.6 ± 408.5	508.8 ± 55.8	399.6 ± 164.1	692.7 ± 276.8	6579.6 ± 1204.2	2791.0 ± 2825.3	671.1 ± 80.4	-

Description: T = stumps, (*) = the same abbreviation as in Table 1. (**) = other than the fuelwood value index, data cited from (Widiyawati & Irawati 2021). (***) = Other than the fuelwood value index, data cited from (Cahyo & Irawati 2020)

aligned with the previous research, which showed a larger composition of stems than branches and leaves (Lukito & Rohmatiah 2013; Karyati et al. 2019). The low number of leaves was due to logging during the dry season when teak trees shed leaves to reduce transpiration. This research grouped commercial and unmerchantable top stems (BA) to distinguish between those used for carpentry and fuelwood. The commercial stem of six and eight-year-old JUN constituted 65.5% and 54.2% of the total biomass per tree, meaning logging waste comprised 34.5% and 45.8%.

The one-factor analysis of variance investigated the effect of age on JUN biomass weight (Table 2). It indicated that age significantly affected the fresh weight of BA, the green moisture content of commercial stems, BA's dry weight, and C's dry weight. The fresh weight of BA in eight-year-old trees (44.6 kg) was higher than in six-year-old (17.0 kg), stemming from the reduced commercial stem part of the trees, thereby retaining a substantial amount of the unmerchantable top biomass. The high fresh weight of BA in eight-year-old trees also correlated with its dry weight because the green moisture content of BA in eight and six-year-old trees was not significantly different.

The green moisture content of six-year-old trees (43.6%) was significantly higher than eight-year-old trees (34.3%). This discrepancy was attributed to the absence of debarking before logging in six-year-old trees, while the eight-year-old trees had undergone debarking 11 months prior to logging. The green moisture content influenced the biomass transportation from the forests because it positively correlated with the biomass weight. However, it negatively correlated with the calorific value; a higher green moisture content led to a lower calorific value (Junary et al. 2015). Sun-drying the biomass before use as fuel could mitigate this higher moisture content. The dry weight of C in eight-year-old trees was significantly higher than in six-year-old trees. Trees accumulated more biomass as they grew.

Oven-dried Density

Table 3 showed that the density for various biomass types of six and eight-year-old JUN trees ranged from 0.51 to 0.83 g/cm^3. Part D of eight-year-old trees had the highest density, while part R of six-year-old trees showed the lowest. Finally, the overall average density across all biomass types was 0.65 g/cm^3. In this research, age did not significantly affect density, while the biomass type significantly affected density. The post hoc tests indicated that the density

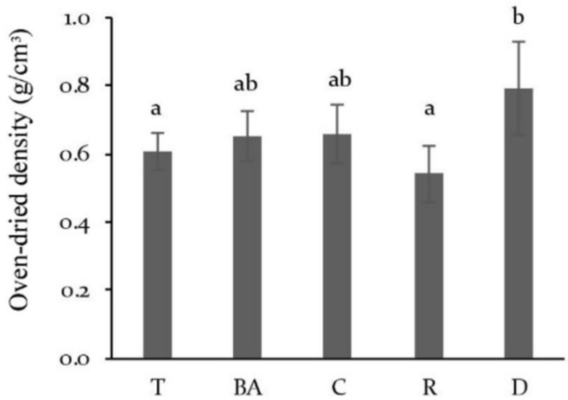

Figure 1. Oven-dried density histogram for several biomass types of JUN trees
Note: Different letters indicate a significant difference at α=5% of the follow-up test results with an HSD value of 0.14. T: stumps, BA: top stems, C: branches, R: twigs, and D: leaves.

of D was significantly higher than R and T. Meanwhile, the density of BA and C did not significantly differ from other biomass types (Figure 1). Leaves had denser cell structures than wood and accounted for the higher density of D. Furthermore, the density value of D fell within the density range of leaves observed in various woody plants (Niinemets 1999). Density reflected the amount of biomass mass per unit volume. As it increased, the energy produced per volume increased and prolonged the combustion process (Kumar et al. 2010).

Ethanol-Toluene Extractive and Klason Lignin Contents

Previous research demonstrated a direct positive correlation between ethanol-toluene extractive and lignin contents with biomass energy characteristics. (Telmo & Laousada 2011; Gruber et al. 2021). The ethanol-toluene extractive content of various JUN biomass types ranged from 3.05% to 10.9% (Table 3). These values were within the ranges of previous research on 11-year-old Jati Plus Perhutani samples (Zulkahfi et al. 2020). The analysis of variance suggested that both biomass types and ages of JUN significantly affected the ethanol-toluene extractive content at the 1% significance level, while their interaction was not significant. Part R of JUN showed the highest ethanol-toluene extractive content, while eight-year-old trees had a higher content than six-year-old trees. Previous research on teak wood also observed higher ethanol-toluene extractive in the basal part compared to the end part (Zulkahfi et al. 2020).

The lignin content in various JUN biomass ranged from 18.1% to 28.0% (Table 3). The analysis of variance showed that both biomass types and ages of JUN significantly affected lignin content at the 1% significance level, while their interaction was not significant. Part T had the highest content, while eight-year-old JUN had higher content than six-year-old trees. The Eucalyptus globulus species also had higher lignin content in older trees (Rencoret et al. 2011). In this research, the lignin content was lower than in the community-managed teak forests in Gunungkidul, ranging from 31.47% to 33.52% (Lukmandaru et al. 2016). There was no correlation between ethanol-toluene extractive, lignin content, and calorific value. This research used relatively young wood with a substantial amount of juvenile wood, leading to glucose-compound extractives with low calorific values.

Proximate Content

The ash content varied across different biomass types, ranging from 0.45% to 10.0% (Table 3). The average ash content for all biomass types was 3.66%. The analysis of variance suggested that biomass types and age significantly affected the ash content at a 1% significance level. The ash content of the T in six-year-old trees, BA and C in six and eight-year-old trees were not significantly different, while they differed significantly from the R and T in eight-year-old trees and D in six and eight-year-old trees (Figure 2). The leaves contained the highest ash, potentially attributed to the tree's ability to absorb nutrients from the soil, transport them through the xylem to the stem,

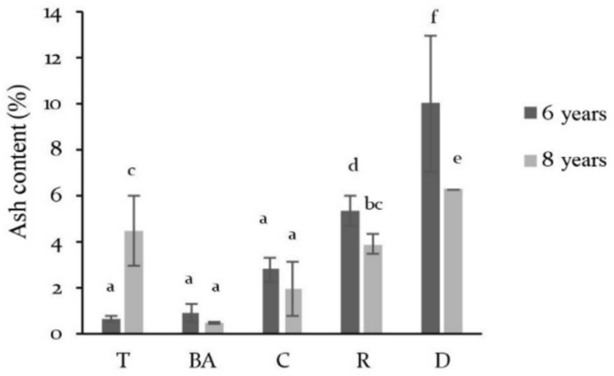

Figure 2. Ash content histogram for several biomass types of six and eight-year-old JUN trees
Description: Different letters indicate a significant difference at α = 5% of the follow-up test results with an HSD value = 3.30. T: stumps, BA: top stems, C: branches, R: twigs, and D: leaves

and ultimately to the leaves. Additionally, it was plausible that rainwater and atmospheric sources contributed to the ash content in leaves. The heightened ash content observed in this research might result from wind-borne dust accumulation on the leaves, as supported by the report of *Ficus capensis* leaves with a similarly high ash content of 11% (Uzoekwe & Mohammed 2015). The ash content of BA aligned with previous research on teak wood from three provenances, ranging between 0.59% and 1.43% (Prasaningtyas & Sulistyo 2014). High ash content in biomass could reduce its calorific value since ash did not convert into energy during combustion. Ash became residual of complete combustion and potentially reduced furnace capacity.

The volatile matter content in various types of JUN biomass ranged from 70.8% to 87.9%. Part C of the six-year-old trees had the highest content of volatile matter, while part D of the eight-year-old trees had the lowest (Table 3). The average volatile matter content across biomass types was 79.7%. The analysis of variance indicated that age and biomass types single-factor significantly affected volatile matter content, while the interaction between these factors was not significant at a 1% significance level. The HSD post hoc test indicated that parts D, T, and R exhibited significant differences in volatile matter content. Part C and T had no significant differences in volatile matter content, while part T had no significant difference with R and BA in volatile matter content. The average volatile matter content of JUN biomass aligned with the volatile matter content of eight tree species cultivated in the Kupang Regency, including Casuarina, Takah, Lamtoro, Turi, Nilotica, Kesambi, and Gmelina (Koeslulat et al. 2016). Logwood's average volatile matter content was 80%, primarily consisting of easily combustible carbonyl and aromatic compounds, suggesting that a higher volatile content made the wood more susceptible to combustion (Hartikainen et al. 2018). However, a higher volatile matter content could reduce the fixed carbon value and affect the high calorific value of the biomass.

The fixed carbon content within different JUN biomass samples ranged from 9.30% to 22.9%. Part D of eight-year-old trees had the highest fixed carbon content, while part C of six-year-old trees showed the lowest (Table 3). The average fixed carbon content across various biomass types was 16.6%. The analysis of variance indicated biomass type and age single-factor, and their interaction significantly affected the fixed carbon content at a 1% significance level. The HSD post hoc test revealed that the fixed carbon content of R, C, and D significantly differed from the stem in six-year-old trees' carbon content. They also significantly differed from all biomass types in eight-year-old trees (Figure 4). The average fixed carbon content was similar to the branch wood carbon content from various tree species (Irawati et al. 2020).

Calorific Value

The calorific values observed in various JUN biomass samples ranged from 4516.4 to 5177.7 cal/g, with an average of 4768,4 kal/g (Table 3). The analysis

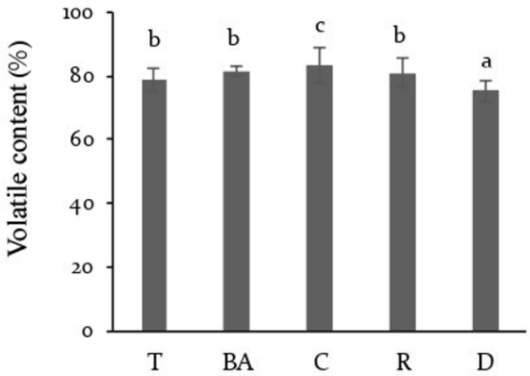

Figure 3. Volatile matter histogram for several biomass types of JUN trees
Description: Different letters indicate a significant difference at α = 5% of the follow-up test results with an HSD value = 3.40. T: stumps, BA: top stems, C: branches, R: twigs, and D: leaves

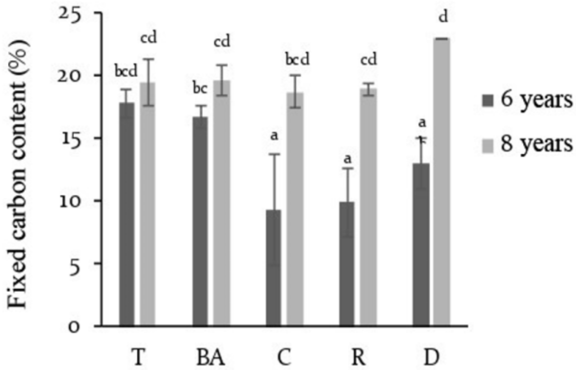

Figure 4. Fixed carbon content histogram of several biomass types in six and eight-year-old JUN trees
Description: Different letters indicate a significant difference at α = 5% of the follow-up test results with an HSD value = 5,70. T: stumps, BA: top stems, C: branches, R: twigs, and D: leaves

of variance indicated that neither the age nor various biomass types significantly affected the calorific values, meaning that all biomass types could become good fuelwood. The calorific values of eight-year-old JUN biomass in this research were higher than *Acacia auriculiformis* and *Acacia mangium* wood aged three years, falling within the range of 3900 to 4200 cal/g (Marsoem & Irawati 2016).

The stem below the branch-free height became the primary commercial product of teak. Other biomass types were considered waste (Lima et al. 2020), and communities surrounding the forests utilized this biomass as fuelwood. In this research, the average dry weight of BA, C, R, and D from six and eight-year-old teak trees was 31.5 and 53.5 kg, respectively (Table 1). The total energy produced from the logging waste of a single tree was determined based on the dry weight and calorific value of each biomass type. The energy generated from logging waste of six-year-old and eight-year-old teak trees was 150.83 and 235.48 kcal, respectively. In comparison, the calorific values of six and eight-year-old JPP trees were 230.60 × 106 MJ/ha and 216.70 × 106 MJ/ha, respectively (Wirabuana et al. 2022).

Fuelwood Value Index

Each biomass type's calorific value, density, and ash content determined the fuelwood value index (Table 3). The fuelwood value index ranged from 399.6 to 6579.6 in six-year-old and eight-year-old trees, with the BA of eight-year-old trees having the highest and the D of six-year-old trees having the lowest values. Furthermore, the average value across all biomass types was 2639.0. The analysis of variance indicated that both the single factor of biomass types and the interaction between the two factors significantly affected the fuelwood value index at the 1% significance level.

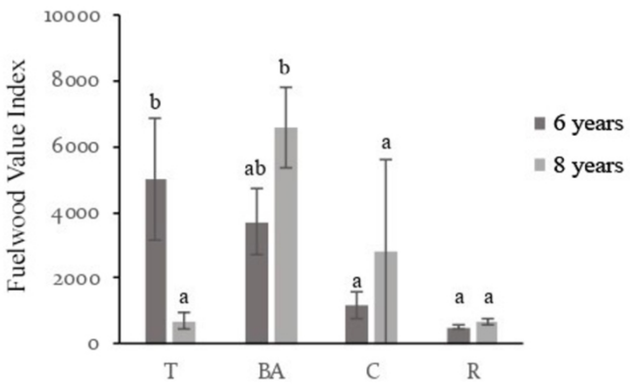

Figure 5. Fuelwood value index histogram of several biomass types in six and eight-year-old JUN trees
Description: Different letters indicate a significant difference at α = 5% of the follow-up test results with an HSD value = 3753,9 T: stumps, BA: top stems, C: branches, R: twigs, and D: leaves

The post hoc test suggested that the BA fuelwood value index significantly differed from other types of biomass. Biomass with a higher fuelwood value index became the preferred fuelwood. Factors like high calorific value, high density, and low ash content influenced this index (Chettri & Sharma 2009; Ojelel et al. 2015). The low ash content and high density of BA in eight-year-old trees were the reasons for attributing the high fuelwood value index. This research recorded an average fuelwood value index higher than three-year-old *Acacia auriculiformis* and *Acacia mangium*, which ranged from 1654 to 3072 (Marsoem & Irawati 2016). Meanwhile, the value fell within the range obtained from 16 wood trees and 23 livestock feed plant species from Sikkim, India (448-22678) (Chettri & Sharma 2009). The highest fuelwood value index recorded in BA indicated that the upper part of the trees was potentially valuable as fuelwood.

Conclusion

In conclusion, the average biomass waste increased as the age of JUN trees increased, ranging between 31.5 and 53.5 kg per tree, with energy values from 150.83 to 235.48 kcal. The BA had low ash content and high density, making it suitable for fuelwood. JUN's extractive and lignin content in this research did not correlate with calorific value. Further, the logging waste from eight-year-old JUN trees exhibited better energy characteristics than six-year-old trees, particularly the BA, with a high fuelwood value index of 6579.6.

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