From Waste to Watts: Investigating Teak Biomass Waste for Bioenergy

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GRAPHICAL ABSTRACT

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The appropriate use of forest biomass can support the transition to a society with clean and renewable energy. In this context, the research aimed to evaluate the waste biomass from *Tectona grandis* L.f. for energy purposes. Seven teak wood waste types were used, accessible from the harvesting stage to wood processing. Physical attributes (moisture and basic density) and proximate analysis (volatile materials, ashes, and fixed carbon content) were evaluated, which were used to estimate the energy attributes (higher, lower, and net heating value and energy density). It was found that most waste components had moisture content averages below 30% and did not differentiate statistically. For the basic density, values varied between 366 and 519 kg.m^{-3}. Proximate analysis and energetic attributes of the teak wastes support its feasibility for bioenergy use, focused on trimmings and thin logs. It was concluded that teak waste has the potential for energy purposes if its specific characteristics are considered and appropriate ways of use and conversion are chosen.

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Keywords: Tectona grandis L.f; Bioenergy; Chemical composition; Heating value

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INTRODUCTION

In the last two decades, global governments have implemented measures to address greenhouse gas (GHG) emissions and climate change (Hoang *et al.* 2022; Malla *et al.* 2022). Proposals have emerged to replace fossil fuels with renewable sources of energy that are both secure and sustainable, capturing widespread interest among scientists. In 2022, World Energy & Climate Statistics indicated that nearly 30% of global electricity consumption came from renewable sources (Enerdata 2023). However, despite the benefits and potential for substituting fossil fuels, renewable sources remain vulnerable to changes in climate, land use, and vegetative cover (Serrão *et al.* 2023). Countries such as Brazil must pay attention to these changes, as they emerge with an electrical matrix that is primarily renewable (> 87%) and with a significant share of hydroelectric plants (Empresa de Pesquisa Energética 2023). Thus, expected precipitation deficits in South America (Grimm 2011; Farinosi *et al.* 2019; Riquetti *et al.* 2020) and deforestation in important Brazilian biomes (Amazon and Cerrado) negatively impact electricity production. Furthermore, the hydrological seasonality regulates the use of water resources (Queiroz *et* *al.* 2019), creating maximum and minimum peaks in energy generation. In this sense, it is essential to diversify renewable sources, also considering their local and seasonal availability.

Brazil is a significant partaker in the bioenergy sector. Among renewable sources, bioenergy contributes 8% to the total share, mainly generating sugarcane bagasse energy (Empresa de Pesquisa Energética 2023). Additionally, there is the potential to enhance the presence of biomass in the energy matrix of developed and developing countries by utilizing waste from planted forests, reinforcing the growing emphasis on building a circular economy, and transitioning towards a decarbonized economy world. In 2022, the total area of trees planted in this country totaled 7.6 million hectares (Indústria Brasileira de Árvores 2023), of which teak (*Tectona grandis* L. f., Lamiaceae Family) occupies 76 thousand hectares. The latest data on generation in tons of waste are from 2018 and indicate that the sector generated 52 million tons of solid waste, of which 36.9 million (70.9%) were generated by forestry activities and 15.1 million (29.1%) by industries (Indústria Brasiliera de Árvores 2020). For teak, biodegradability is slow (Gupta *et al.* 2019), and the waste generated can be environmentally passive and difficult to manage. Using these residues in bioenergy production is a sustainable and economically advantageous option.

According to previous research, wood from young trees has a higher heating value than other hardwoods, indicating potential for bioenergetic use (Silva *et al.* 2015). There is also the prospect of new compounds from the pyrolysis of teak sawdust. Bardalai and Mahanta (2018) performed pyrolysis at 450 ºC to investigate the physicochemical properties of bio-oil for its application in engines, and Balogun *et al.* (2014) verified several valuable chemical compounds through gas chromatography–mass spectrometry analysis. Even though the teak is a vital timber species established throughout the tropics (Gupta *et al.* 2019; López-Tobar *et al.* 2019), few studies have been conducted concerning its physical properties for plantations in Brazil (Chagas *et al.* 2014). Studies based on chemical and energy properties are still lacking, a gap that this research aims to help fill. Therefore, this study aimed to evaluate the potential of the *Tectona grandis* L.f. wood wastes for bioenergy generation through the hypothesis that the different wastes have physical-chemical, and energetic attributes compatible with distinct conversion energy pathways. Based on the results, this study provides valuable insights for developing renewable energy alternative sources by reusing wood residues from planted forests, considering their potential positive impacts on the energy and environmental sectors.

EXPERIMENTAL

Location of the Research Area

The field data was collected in the storage yard and teak plantation area. The farm's headquarters is located at Capitão Poço, Pará – latitude 02°21'17" S and longitude 47°22'19" W (Fig. 1). The property has a total area of 1,300 hectares, of which 833 ha are designated for planting teak for lumber production.

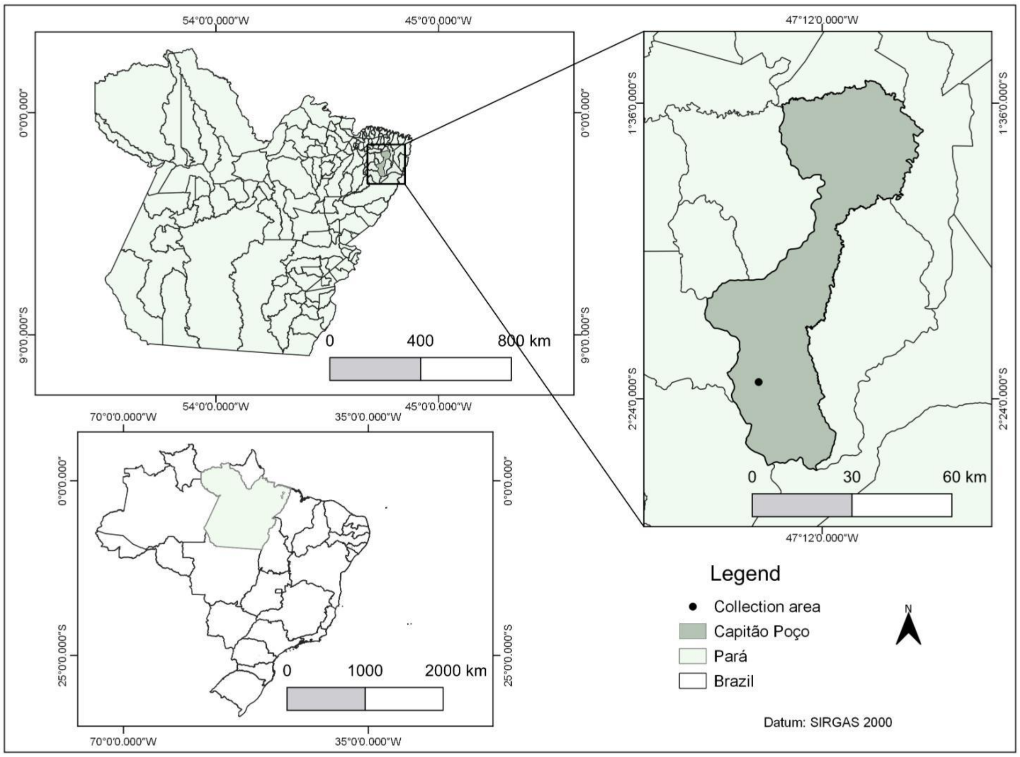
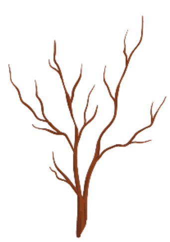
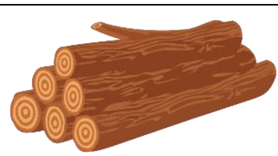


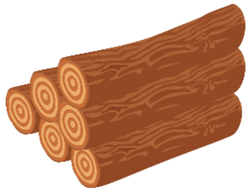
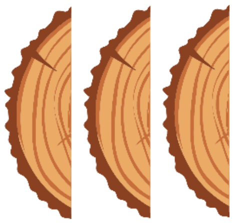
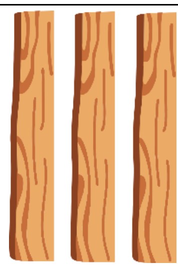
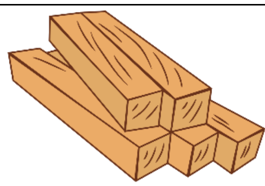
Fig. 1. The location map of the municipality of Capitão Poço, Pará, Brazil

Collection and Preparation of Samples

Table 1 presents the characteristics of the residual biomass studied and the collection sites. The research used seven wastes available at different times of teak wood processing, from the harvesting stage to the timber processing.

Table 1. General Information on the Teak Wastes Studied

Wastes (Code)	General information	Collection Sites
 Crown (CRW)	It comprises thin and thick branches and stems above the commercial height limit established for the forest stand. Coming from thinned individuals	Recently thinned forest
 Thinned logs (THN)	Logs with smaller diameters than those needed for mechanical processing. Storage in small decks for approximately six months	Logging Decks

 Log tops (LGT)	It comes from the standardization cut of logs suitable for sawmill activities	Logging Decks
 Slabs (SLB)	It results from sawing, has a flat face and a curved one, presenting a crescent shape	Logging Decks
 Edgings (EDG)	It comes from the cut of the gang saw, used to standardize the lateral edges. They are thin cuts using circular saws.	Logging Decks
 Trimming (TRM)	It comes from cutting the trimmer, which is used to adjust the length of the lumber using circular saws.	Logging Decks
 Deteriorated logs (DTR)	It comes from individuals thinned in forest harvesting activity. It remained in field conditions for approximately 2.5 years	Nearby secondary roads in the forest stand

Ten repetitions were used to prepare the specimens for the physical tests. Many pieces were weighed in a known volume container for biomass from sawing. One piece was collected from each weighing to compose the repetitions. For the thinned and log tops, 10 logs were used (each one considered a repetition), where three discs (base, middle, and top) were removed and later transformed into wedges to perform the necessary procedures. Ten trees were used to sample the crown, each considered a repetition. The aim was to sample thin and thick branches and stems above the commercial height limit established for the stand. The authors also used small wedges or discs. Each residual component under this study was reduced to chips for the chemical and energetic determinations, and a composite sample was formed, representing the repetitions mentioned above. After that, the biomass was reduced in a Willey-type mill and then classified into 40- and 60-mesh sieves, using the smaller material retained.

Waste Biomass Characterization Tests

Next, the physical (moisture content and basic density), chemical (volatile materials, ashes, and fixed carbon), and energetic parameters (higher, lower, liquid heating value, and energetic density) were analyzed. The gravimetric method was used to determine the moisture content (wet basis), as described in ASTM D1762-84 (2021). The specimens were dried in an oven with forced air circulation at 103 ± 2 °C until constant mass. The mass was considered constant when the difference between two consecutive weightings, with a difference of 24 h, was less than 1 %. The basic density was determined based on NBR 7190 (Associação Brasileira de Normas Técnicas 1997). The specimens were saturated in water with a desiccator and vacuum pump assistance until they reached constant volume. The saturated volume was obtained on a hydrostatic scale by weighing (based on the Archimedes Principle). Subsequently, drying was performed in an oven at 103 ± 2 °C until the mass was stabilized.

The authors used the ASTM D1762-84 (2021) standard for the proximate analysis to determine the volatile matter content, ashes, and fixed carbon. The heating values were estimated from proximate analysis by Eqs. 1, 2, and 3, obtained by modeling the chemical composition and calorific value of several solid biomass with an absolute error of 3.74% (Parikh *et al.* 2005),

$$HHV = 0.3536 \text{ x } CF + 0.1559 \text{ x } VM - 0.0078 \text{ x } ASH \quad (1)$$

$$LHV = PCS - (2.5116 \text{ x } 0.09 \text{ x } H) \quad (2)$$

$$NHV = (PCI \text{ x } (1 - (0.01 \text{ x } U))) - (2.5116 \text{ x } 0.01 \text{ x } U) \quad (3)$$

where *HHV* is the higher heating value ($MJ.kg^{-1}$), *LHV* represents the lower heating value ($MJ.kg^{-1}$), *NHV* is the net heating value ($MJ.kg^{-1}$), *FC* is fixed carbon (%), *VM* is volatile matter content (%), *ASH* is ash content (%), *H* is hydrogen content (%), and *MC* is moisture content (%).

The authors consider the hydrogen content to be 6.42%, as obtained from studies of teak individuals of 5 and 8 years (Blanco-Flórez 2012). The authors determined the energy density (ED) by the product between the lower calorific value in $MJ.kg^{-1}$ and the basic density in $kg.m^{-3}$.

Experimental Design and Data Analysis

The random balance design was adopted, with seven treatments, ten repetitions for the physical parameters, and six repetitions for the variables that integrated the chemical and energetic analyses. Waste biomass was considered as a factor. The data residues were performed to the Shapiro-Wilk and Bartlett tests at 95% probability. After proving normality and homogeneity of variance, univariate analysis of variance (ANOVA) was performed and the Tukey test was applied at 5% significance for multiple comparisons of means. The transformation attempted to normalize non-normally distributed and heteroscedastic data, and in cases where the behavior persisted, the authors adopted the non-parametric Kruskall-Wallis test and the Dunn test with Bonferroni correction.

RESULTS AND DISCUSSION

Physical Attributes and Proximate Analysis

In general, teak waste showed an average of 27.9%. As observed in Fig. 2A, log tops contained a higher moisture content, corresponding to 45.9%, followed by the slab with 36.8%. The other components had averages below 30% and did not differentiate statistically. Three groups were distinguished for the basic density values, which ranged between 519 and 366 kg.m^{-3}. Moisture content (MC) is one of the main factors limiting the application of biomass for energy purposes because of its implications on transport costs, storage difficulties, and thermal efficiency reduction during energy conversion (Qi *et al.* 2021). Water in biomass affects its energy conversion through thermochemical pathways. A high moisture content can cause incomplete combustion and undesirable reaction products, increasing the emission of pollutant gasses (Geronimo *et al.* 2022). Therefore, values of 30% or less are more suitable for conversion (Zha *et al.* 2023). For the production of compacts (briquettes and pellets), there is also an ideal range of MC. Excess moisture content can cause explosions due to steam formation. However, excessively dry raw material makes the bonding mechanisms between the particles difficult, as its plasticity is reduced, and friction during compaction increases (Song *et al.* 2023). According to the literature, MC between 5 and 15% is ideal (Nath *et al.* 2023).

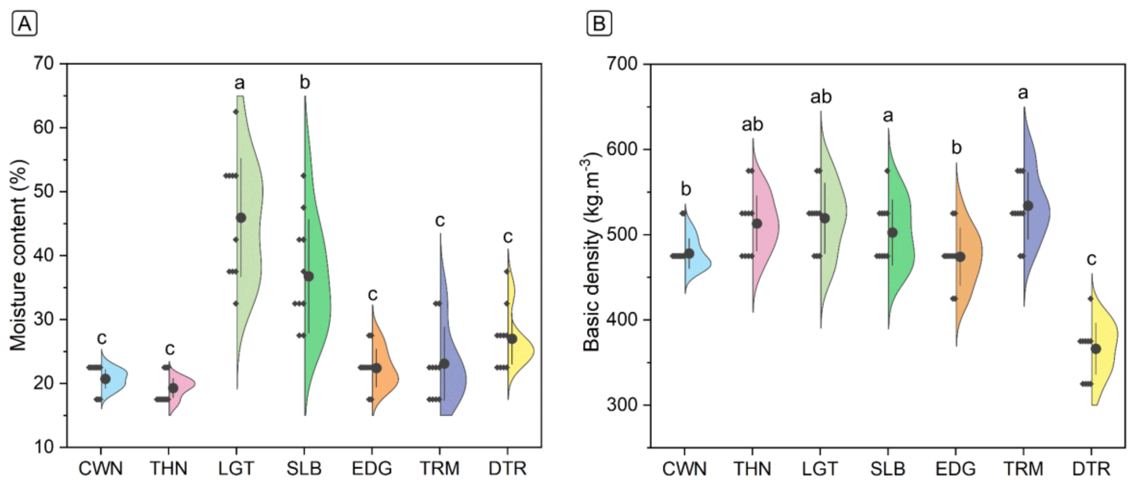


Fig. 2. Physical attributes of the different teak wastes: (A) moisture content (%) and (B) basic density (kg.m^{-3})

The moisture content is sensitive to climatic conditions during the storage period due to the hygroscopic nature of the wood, that is, its capacity to retain and lose water to the environment. As a rule, there is a hygroscopic equilibrium point, where each pair of temperature and relative humidity values of the air in the environment will provide a certain moisture content in the wood (Riaz *et al.* 2022). When considering that biomass' different sizes and storage periods influence the speed and intensity of changes to their properties (Brand *et al.* 2014a), the heterogeneity of values and formation of statistically distinct groups is understandable for this research. Smaller biomass pieces, such as edgings and trimming, were observed to have the lowest moisture content. A similar effect was observed for the crown, which, although it had a larger volume than the wastes mentioned above, had diameters smaller than 10 cm and a relatively long length of stay in the field. The thinning and the deteriorated logs were large pieces, and it is not possible to attribute their low contents to the volume of the pieces, but the storage time, from approximately six months to more than two years, respectively, may have contributed to this moisture content. All the components studied presented lower moisture content than those found in residual biomass already used for bioenergy generation. For example, the branches of *Eucalyptus* sp., whose average value was 48.3% (Santiago and Rezende 2014), and the crown, acicules, and twigs of *Pinus taeda*, with a moisture content varying between 56 and 65% (Brand *et al.* 2014b; Ferreira *et al.* 2016), even though those values are from newly felled trees.

The teak waste was found to have an average basic density of 484 kg.m^{-3}. In Fig. 2B, it can be observed that all wastes, except for deteriorated logs, had densities ranging between 584 and 442 kg.m^{-3}, which was similar to that of teak wood aged 5 and 8 years, respectively (Silva *et al.* 2015). It is natural that density increases with age (Costa *et al.* 2020); however, the difference between the values obtained in this research cannot be exclusively explained by this factor. The authors know that the different biomass from sawing does not pass through a grouping criterion; that is, wastes from trees of different ages were placed together, making it only possible to identify the age of the top and thinned logs (8 years). In contrast, the proportion of juvenile and adult wood within the biomass studied could help to understand the values found. Garcia and Marinonio (2016) observed that the basic density decreased in the pith-bark direction for teak cultivated at 5 x 2 m^2 spacing. Such variation may result from the wood anatomy and imply physical variations as well as density (Lima *et al.* 2011). This hypothesis could only be confirmed by studies of wood from the wastes.

The edgings and crowns had a larger fraction of juvenile wood because they were removed from the periphery of the log or are younger components. However, the trimmings came from pieces made in more central regions. The thinned logs, log tops, and slabs represent juvenile and mature wood material, which could be inferred from their average basic density values. The deteriorated logs presented lower basic density, indicating that the deterioration level could influence its structural components (lignin, cellulose, and hemicelluloses) and decrease its mass per volume unit.

It is known that the higher the basic density, the greater the availability of energy per volume unit of wood (Protásio *et al.* 2019). Thus, the biomass from the group with higher average values has the potential for charcoal production. This biofuel is in high demand by the steel industry, which already consumes charcoal from eucalyptus plantations with basic densities similar to the values obtained in this research. Studies with clones of the genus *Corymbia* and *Eucalyptus* showed values between 400 and 520 kg.m^{-3} (Lopes *et al.* 2017), and for clones of *Eucalyptus urophylla* x *Eucalyptus grandis*, this value was even lower, from 360 to 410 kg.m^{-3} (Sereghetti *et al.* 2015). Due to lower basic density and smaller size, other biomasses could produce other solid biofuels, such as briquettes and pellets. To verify the economic feasibility of this use, it is necessary to consider many variables, such as quantity, location, availability, and energy quality, of the biomass (Nones *et al.* 2017). The present research acts in the qualitative characterization of these biomasses.

Figure 3 shows the values obtained from the proximate analysis of the biomass studied. Tukey's test (5% probability) differentiated three groups for VM and four for ASH, which did not occur for the FC characteristic, even the analysis of variance indicating a statistical difference between the different biomasses.

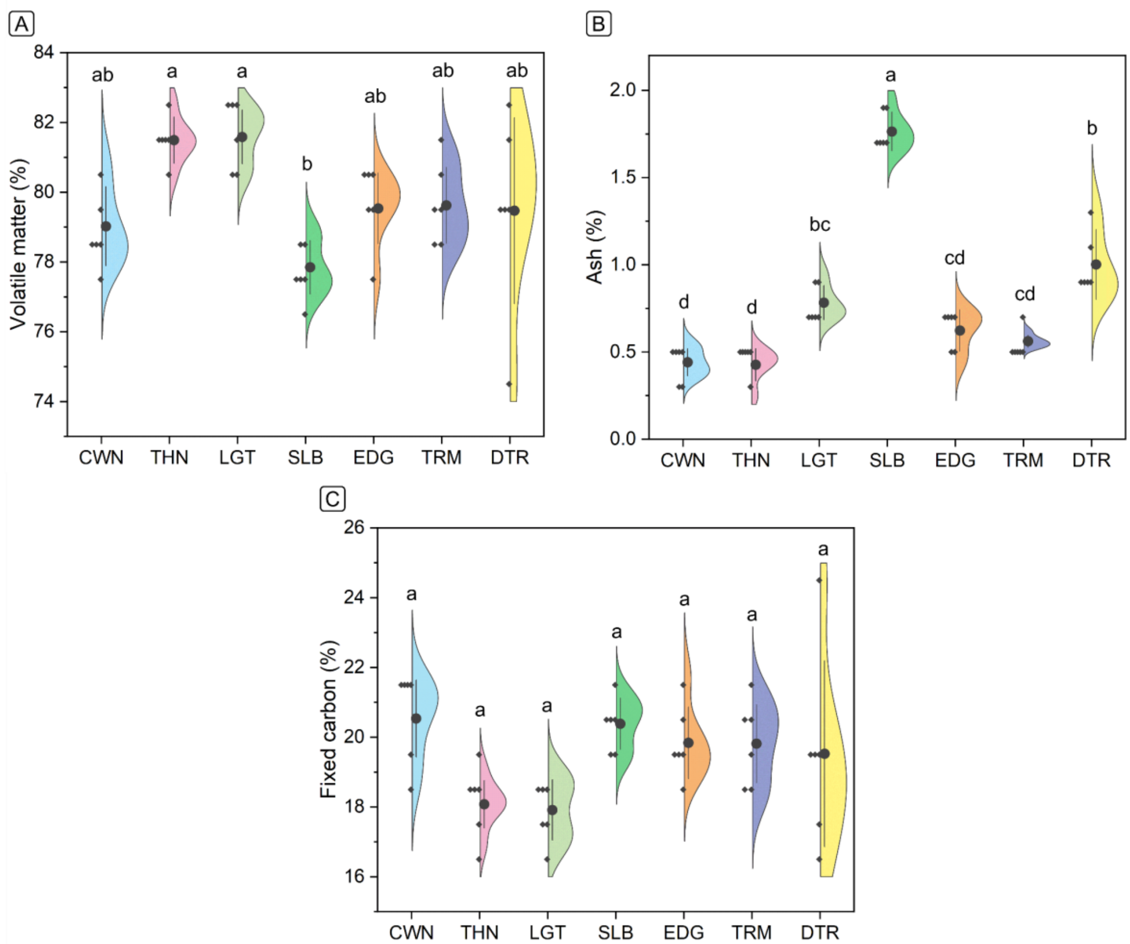


Fig. 3. Proximate analysis of the different teak wastes: (A) volatile matter (%), (B) ash (%), and (C) fixed carbon (%)

The volatile matter content is indicative of the ease of ignition of the biomass, the stability of the flame, and its burning rate (Souza *et al.* 2016). In this research, the logs for thinned logs and log tops had higher percentages, followed by trimmings, edgings, deteriorated logs, and crowns. All averages of the biomass cited were similar to those found for teak 5 and 8 years old (Silva *et al.* 2015) and were in line with those described in the study by Teixeira *et al.* (2016) when evaluating *Eucalyptus* sp. It is possible to verify that the slabs presented lower VM and differed statistically from the group with a higher mean. This difference can be explained by the higher percentage of ash in this biomass. One of the reasons for the increase is associated with the number of impurities from dust and bark, which participate in the protection of the plant and are susceptible to higher inorganic material incrustation (Brand 2010).

The other biomass presented ash levels below 1% and were within the range found for teak wood: 0.98 to 0.40% (Blanco-Flórez 2012; Silva *et al.* 2015) and close to that for bark and wood of other forest species, such as *Eucalyptus* and *Corymbia* clones, with ranges from 0.54 to 0.31% (Lopes *et al.* 2017). It is worth remembering that the low ash content is positive for energy purposes because the mass of inorganic solid residue is constituted of minerals that do not act in the energy generation process and, instead, can reduce it (Deng *et al.* 2020), as well as damage the equipment used in the biomass conversion processes (Garcia and Marinonio 2016). For charcoal, biomass with low levels of minerals is also preferred, as these will produce a biofuel of higher mechanical quality, *i.e.*, less friable and prone to fines production (Souza *et al.* 2016).

Fixed carbon represents the fraction of biomass free of moisture, volatiles, and ash. For the use of biomass in direct combustion, co-incineration, and charcoal production, high values of FC are required (Soares *et al.* 2014). Combustible materials with high fixed carbon and lower volatile values tend to burn more slowly (Brand 2010). Therefore, the VM/FC ratio assists in the knowledge about the biomass burning time. For chips and sawdust of *Pinus* sp., the fixed carbon ranged from 12.9 to 17.4% (Protásio *et al.* 2013; Oliveira *et al.* 2017); these values are lower than those found in this study.

Similarly, the FC of *Eucalyptus* sp. sawdust was observed at 14.0% (Protásio *et al.* 2013). The fixed carbon obtained by Teixeira *et al.* (2016) was about 19.3%, based on studies with *Eucalyptus* sp. harvest residues. Eloy *et al.* (2015), who investigated the bark, branches, and leaves of *Eucalyptus grandis*, found an average FC of 21.2, 18.9, and 20.9%, respectively. These values were higher than those of biomass derived from sawing but are still within the range observed for the other teak residues studied. These practical considerations underscore the importance of understanding and optimizing the fixed carbon content in biomass to meet the specific demands of different conversion processes and energy applications.

Energy Attributes

The estimated energy attributes are presented in Fig. 4 below. The Kruskall-Wallis test indicates a statistical difference between HHV values. Dunn’s test with Bonferroni correction performed the pairing of all wastes, indicating that only crown–log tops and crown–thinned logs had different HHV values. The other pairings did not show a significant difference between them. It was observed that the lower heating value presented the same behavior due to its closed relationship.

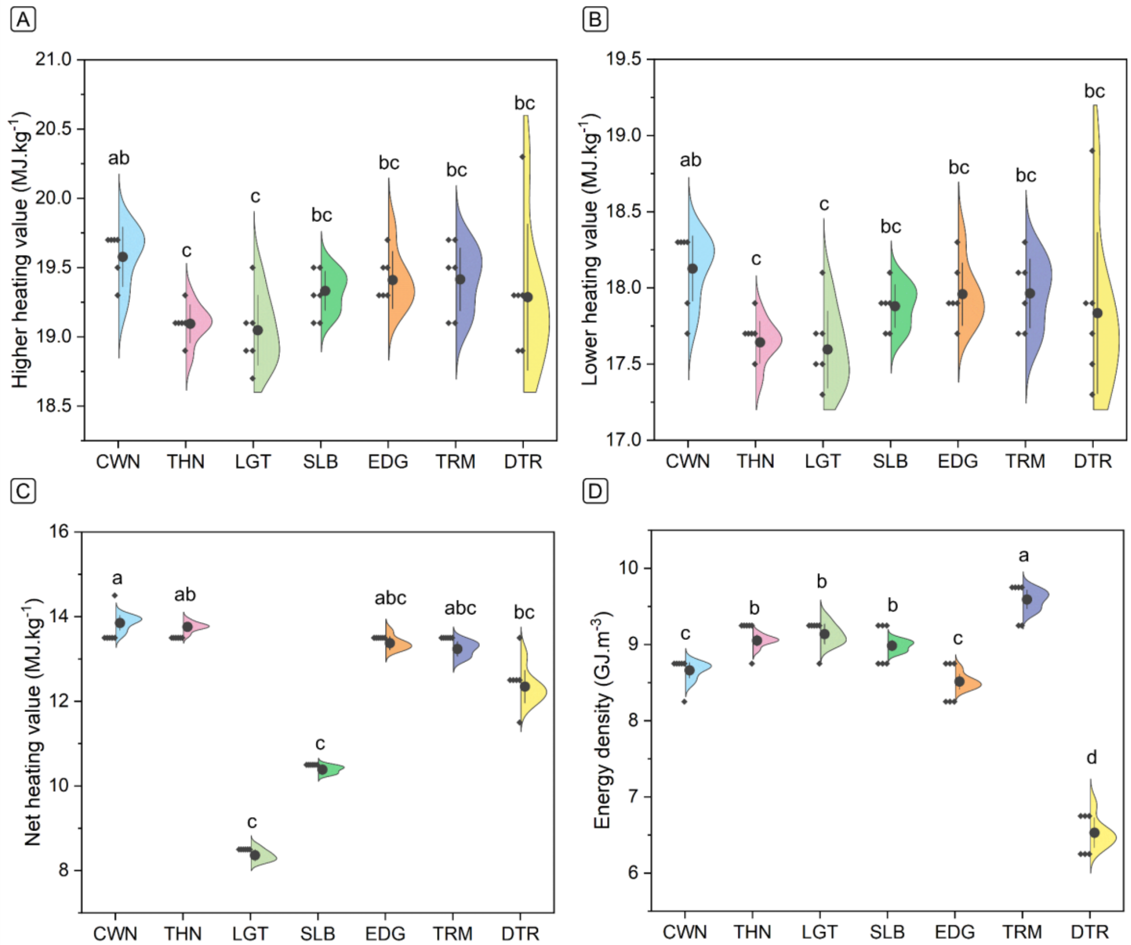


Fig. 4. Estimated energy attributes for the different teak wastes, where (A) higher heating value (MJ.kg^{-1}), (B) lower heating value (MJ.kg-1), (D) net heating value (MJ.kg^{-1}), and (E) energy density (GJ.m^{-3})

According to the studies of Blanco-Flórez (2012), the average HHV of young teak individuals was 19.9 MJ.kg^{-1}, and Silva *et al.* (2015) found an average of 19.2 MJ.kg^{-1}. The teak wood analyzed in this study presented an overall average of 19.3 MJ.kg^{-1}. For teak wood sawing wastes, an average of 19.9 MJ.kg^{-1} was also observed (Balogun *et al.* 2018). The behavior was similar to wastes from the sawing of *Pinus* sp. (19.8 MJ.kg^{-1}) (Oliveira *et al.* 2017). All values were close to those obtained in this research — between 19.7 and 19.1 MJ.kg^{-1} (Appendix). When evaluating the potential of *Eucalyptus* sp. forest wastes for thermal and electric energy generation, Santiago and Rezende (2014) obtained higher values than the present study, with an HHV of 20.1 and LHV of 18.8 MJ.kg^{-1}. FC positively affected CWR and EDG wastes but was not responsible for the statistical differentiation into a group with higher HHV for TRM and DTR. In addition, these wastes also presented ash levels between 0.56 and 1%, which may have favored a slight decrease in the HHV and LHV estimates. Regarding the NHV, higher averages for the crown were observed, followed by the logs destined for thinning, trimmings, and edgings. The other biomass types differed statistically, forming distinct groups, and drew attention to their negative impact, as they exhibited the lowest values. This observation underlines the direct influence of elevated moisture content on NHV, emphasizing the practical importance of effectively controlling and managing moisture content in biomass to optimize its heating potential.

The energy density differed in four groups: the highest average was observed for trimmings, with 9.59 GJ.m^{-3}; followed by slabs, thinned and log tops, with values between 9.14 to 8.98 GJ.m^{-3}; crown and edgings, with amplitude from 8.66 to 8.56 GJ.m^{-3}; and deteriorated logs with 6.53 GJ.m^{-3}. For *Eucalyptus benthamii*, at five years, the energy density obtained was 9.23 GJ.m^{-3} (Silva and Silva 2016), which was close to the highest mean values of ED found for the teak wastes studied. In the studies of Jesus *et al.* (2017), which evaluated the energy potential of five species of *Eucalyptus*, the average ED was 6.57 GJ.m^{-3}, which is lower than all the averages mentioned above. In general, basic density values favored energy density, as expected. However, for SLB, although DB values are statistically equal to TRM, the ash content influenced the LHV and, consequently, its final ED value. These results provide valuable insights for selecting and optimizing residual biomass from planted forests for its efficient use as an energy source.

Practical Applications and Future Research

Teak, renowned for its hardwood properties, generates substantial residues across various industries, which can be transformed into a source of clean and accessible energy, contributing to environmental sustainability and addressing energy access challenges (Munsin *et al.* 2022). Using teak residues for energy generation is a practical strategy aligned with the Sustainable Development Goals (SDGs). The commitment to Climate Action (SDG 13) is strengthened by employing teak residues for energy generation, reducing reliance on non-renewable sources, mitigating greenhouse gas emissions, and facilitating the transition to a low-carbon economy. Embracing the circular economy model, in harmony with Responsible Consumption and Production (SDG 12), redefines teak residues, initially considered waste, as valuable resources for energy production, optimizing resource efficiency and minimizing environmental impacts.

Future research should explore innovations to enhance the circular economy, investigating biomass valorization techniques to diversify the applications of teak residues and potentially generate high-value bio-based products. Through collaborative partnerships between teak waste producers and energy-intensive industries, the emphasis on industrial symbiosis can optimize resource utilization, promoting mutually beneficial relationships and reducing the overall environmental impact (Saghafi and Roshandel 2024). Given the challenges of climate change, it is crucial to concentrate research efforts on developing climate-resilient energy systems. Evaluating the adaptability and sustainability of teak waste-based systems in the face of evolving climatic conditions is essential to ensure long-term viability. Furthermore, analyzing the social implications of teak residue utilization in local communities is imperative. A comprehensive understanding of socio-economic benefits and potential challenges is necessary to ensure that energy projects meet community needs and contribute positively to local and regional development.

CONCLUSIONS

1. The pathway to converting teak waste into bioenergy must consider the different characteristics of each waste.
2. Moisture content higher than 30% directly affects the waste combustion performance.

3. The basic density of all components follows the range found for other biomass for energy purposes, except for deteriorated logs.
4. Ash content below 2% of the waste studied implies better conversion equipment performance into other biofuels and efficiency in direct burning.
5. The fixed carbon content indicates potential for co-firing and charcoal production.
6. Smaller pieces of wastes (crown and edgings) with lower basic density are better suited for producing dense biofuels.

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APPENDIX

Supplementary Information

Table S1. Physical Attributes of the Different Teak Wastes

Wastes	Codes	Average	
		MC (%)	BD ($kg.m^{-3}$)
Crown	**CWN**	20.72c	477.89b
Thinned Logs	**THN**	19.28c	513.08ab
Log Tops	**LGT**	45.93a	519.29ab
Slabs	**SLB**	36.75b	502.46a
Edgings	**EDG**	22.40c	474.15b
Trimming	**TRM**	23.09c	533.90a
Deteriorated Logs	**DTR**	26.97c	366.12c

MC = Moisture content, BD = Basic density; Averages followed by the same letter do not differ by the Tukey's test ($p > 0.05$)

Table S2. Proximate Analysis of the Different Teak Wastes

Wastes	Codes	Average		
		VM (%)	ASH (%)	FC (%)
Crown	**CWN**	79.02ab	0.44d	20.54a
Thinned Logs	**THN**	81.50a	0.42d	18.07a
Log Tops	**LGT**	81.59a	0.78bc	17.91a
Slabs	**SLB**	77.85b	1.76a	20.38a
Edgings	**EDG**	79.54ab	0.62cd	19.83a
Trimming	**TRM**	79.62ab	0.56cd	19.81a
Deteriorated Logs	**DTR**	79.47ab	1.00b	19.52a

VM = Volatile matter content, ASH = Ashes, FC = Fixed carbon; Averages followed by the same letter do not differ by the Tukey's test ($p > 0.05$)

Table S3. Proximate Analysis of the Different Teak Wastes

Wastes	Codes	Median		
		HHV (MJ.kg^{-1})	LHV (MJ.kg^{-1})	NHV (MJ.kg^{-1})
Crown	**CWN**	19.66ab	18.21ab	13.92a
Thinned logs	**THN**	19.11c	17.66c	13.77ab
Log tops	**LGT**	19.00c	17.55c	8.34c
Slabs	**SLB**	19.36bc	17.90bc	10.40c
Edgings	**EDG**	19.37bc	17.92bc	13.34abc
Trimming	**TRM**	19.45bc	18.00bc	13.26abc
Deteriorated Logs	**DTR**	19.24bc	17.79bc	12.31bc

HHV, higher heating value, dry basis; LHV, lower heating value; NHV, net heating value; ED = energy density. Medians followed by the same letter do not differ by the Dunn test with Bonferroni correction ($p > 0.05$).

Table S4. Estimated Energy Density for the Different Teak Wastes

Wastes	Codes	Average
		ED (GJ.m^{-3})
Crown	**CWN**	8.66c
Thinned logs	**THN**	9.05b
Log tops	**LGT**	9.14b
Slabs	**SLB**	8.98b
Edgings	**EDG**	8.52c
Trimming	**TRM**	9.59a
Deteriorated Logs	**DTR**	6.53d

ED = Energy density; Averages followed by the same letter do not differ by Tukey's test ($p > 0.05$).