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Effect of Torrefaction Treatment in Energy Content Enhancement of Solid Fuel Properties from Teak Biomass Waste

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Abstract

Torrefaction of biomass produces high-grade solid biofuel from woody biomass or agricultural waste, resulting in high-quality solid biofuel. The study aims to enhance the energy content and efficiency of solid biofuel from waste teak biomass, addressing global energy needs and sustainable alternatives. A 60.8-liter reactor carbonized 5 kg of biomass per batch at 350°C and 400°C, with 40 minutes and 1 hour of residence time. Torrefied biomass was collected and characterized for energy content. Increases in torrefied temperature (TT) and residence time (RT) lead to a significant increase of 15 – 50 % in total carbon content while decreasing hydrogen, oxygen, and moisture content compared to untreated biomass. The study reveals that the energy yield of torrefied biomass is higher than its mass yield and that increasing TT leads to an increase in its bulk density content. The study found that torrefied products had heating values up to 70% higher than unprocessed biomass and a maximum calorific value of around 30 MJ/kg. This research suggests that the solid fuel produced could potentially reduce the release of pollutants into the atmosphere compared to fossil fuels. The biomass teak sample under examination has shown significant potential for efficient energy generation and combustion applications.

Keywords

Energy content, teak biomass, solid biofuel, carbon content, heating values.

1. Introduction

Renewable energy sources have been the subject of much research due to the growing worldwide need for energy, environmental concerns, and the need for sustainable alternatives.

Natural replenishment, a process facilitated by renewable energy sources like biomass, geothermal, solar, hydro, and wind, can occur spontaneously and rapid (Güleç et al., 2018; Tilahun et al., 2021; Ibitoye et al., 2022). Renewable energy sources are environmentally friendly alternatives to traditional fossil fuels due to their minimal emissions and increased efficiency and cost-effectiveness (Chin et al., 2017; Uddin et al., 2019; Gaurav et al., 2020). Mixed sawdust, residual crops, and forest debris create biomass solid fuels like briquettes and pellets, which are denser and more energy-dense than the original biomass (García et al., 2020). Biomass solid fuels, similar to traditional charcoal and coal briquettes, offer advantages over fossil fuels due to their natural origins and smaller carbon footprint, reducing the use of non-renewable energy products (Yoo et al., 2019; San-Miguel et al., 2022).

Waste woody biomass is a plentiful and frequently underused resource that comes from a variety of forestry, agricultural, and industrial operations. At a biorefinery, woody biomass is transformed into valuable products like polymers, bio-plastics, char, pellets, and acids as well as useful energy forms like solid, liquid, or gaseous fuels (Basu, 2018; Bhar et al., 2022). Biorefineries convert biomass into electricity, value-added chemicals, and fuels using biomass conversion technology (Nieto et al., 2019; Qian et al., 2020). Wood, municipal solid waste, and other biomass sources are abundant, sustainable energy sources. Ibitoye et al., (2023) examined the impact of biomass sources and processing techniques on solid fuel microstructural characteristics. Wood is the primary biomass source, with chemical makeup affecting thermal decomposition and conversion technologies. Bamboo is a potential energy source, but a stable supply is needed (Chin, et al., 2017; Heredia et al., 2020).

A solid, energy-dense product with better fuel qualities is produced by the process of torrefaction, which includes heating biomass in a low oxygen atmosphere. Torrefaction of biomass is a thermal process that produces high-grade solid biofuel from various types of woody biomass or agricultural waste (Tan et al., 2015; Umenweke et al., 2022; Uzun et al., 2017). According to Wild and Calderon (2021), the outcome of preheating biomass is a solid biofuel that is homogeneous, stable, and of the highest caliber. For optimum energy production and enhanced fuel qualities, the torrefaction reactor's design is crucial. The energy content of goods made from torrefied biomass is predicted using both proximal and ultimate data analysis, a field of study that is growing geometrically. Proper usage of torrefied biomass in industrial applications requires accurate assessment of the heating value of the material (Tan et al., 2015; Razi et al., 2018; Taki, M and Rohani, 2017). Statistical and artificial intelligence (AI) methods offer an alternate method for estimating the heating value from the proximal and ultimate analysis of the torrefied biomass (Tumuluru et al., 2011; Ighalo et al., 2020; Manouchehrinejad et al., 2021).

Relationships between the proximate analysis and ultimate analysis data, such as moisture, volatile matter, fixed carbon, hydrogen, nitrogen, sulphur, oxygen, and ash content, have been established using machine learning models, such as artificial neural networks, random forests, and linear regression, in order to predict the heating value of the torrefied biomass (Ronsse et al., 2015; Rasi et al., 2018 and Taki et al., 2022; Cahyanti et al., 2020; Cai et al., 2017). A viable technique for converting low-quality biomass into high-energy-density feedstock is torrefaction (Uzun et al., 2017; Chen et al., 2015). Even though torrefaction has advantages, the existing reactor design concepts need to be modified in order to improve the process' productivity and efficiency. The goal of the current study was to increase the energy content and efficiency of the teak biomass that had been torrefied.

Figure 1: Teak plants

2. Materials and Method

2.1 Materials preparation and torrefaction experimental procedure

The Figure 2 teak wood chips (TW) were sun-dried for seven days in an ambient atmosphere after procured locally to reduce the moisture content to 2–4% weight percent. 5 kg of biomass were carbonized every batch using a 60.8liter torrefaction reactor. In a fixed bed batch type torrefaction reactor, the dried biomass was weighed and torrefied for 40 minutes and an hour, respectively, at different temperatures of 350 °C and 400 °C, taking into account the residence temperature (RT) influence on the torrefied biomass waste. Throughout the carbonation process, oxygen was kept out of the reactor chamber and no heat was lost or gained.

The test setup for the torrefaction reactor is seen in Figure 3. A 3.0kilogram biomass sample (TWS) with temperatures ranging from 350 to 400 degrees Celsius was manufactured, mechanically weighed, and labelled TWS350 and TWS400, respectively. Each sample was manually fed into the reactor chamber between 350 and 400 °C. The experimental setup was erected without any air leaks or vapour leaks. A K-type thermocouple was installed to keep an eye on the reactor chambers inside temperature. During operation, the reactor used liquified petroleum gas as a power source, internally heating the feedstock, with the temperature controller pre-set at 300 °C. The reactor's connection to the power supply was cut off when the controller activated at 350 °C. After allowing the torrefied biomass feedstock to cool for 40 minutes (RT40 minutes), the resultant torrefied biomass, which is seen in Figure 4, was removed from the chamber and labelled as TWS350oC at RT 40 minutes. For TWS-350 oC at RT 1 hour, TWS-400 oC at RT 40 minutes, and TWS-400 oC at RT 1 hour, a similar experimental approach was conducted.

Proximate, ultimate, and elemental analysis were used to describe the solid fuel's characteristics. Samples T1 through T5 of teak wood biomass were weighed and placed in crucibles and heated to 110°C for an hour. It was allowed to cool in a desiccator to room temperature. The samples devoid of moisture T1–T5 wood biomass was fed into a closed crucible that was put in a muffle furnace. The crucible was heated to 1000°C for seven minutes, and after that it was allowed to cool in a desiccator to room temperature. The experimental flowchart is depicted in Figure 5.

Fig. 2: Teak Wood

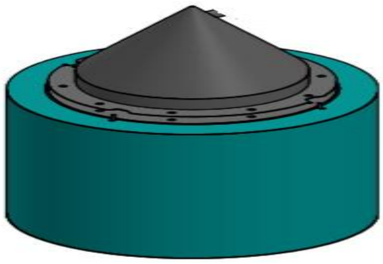

Fig. 3: Fixed bed batch reactor

Fig 4: Torrefied Teak

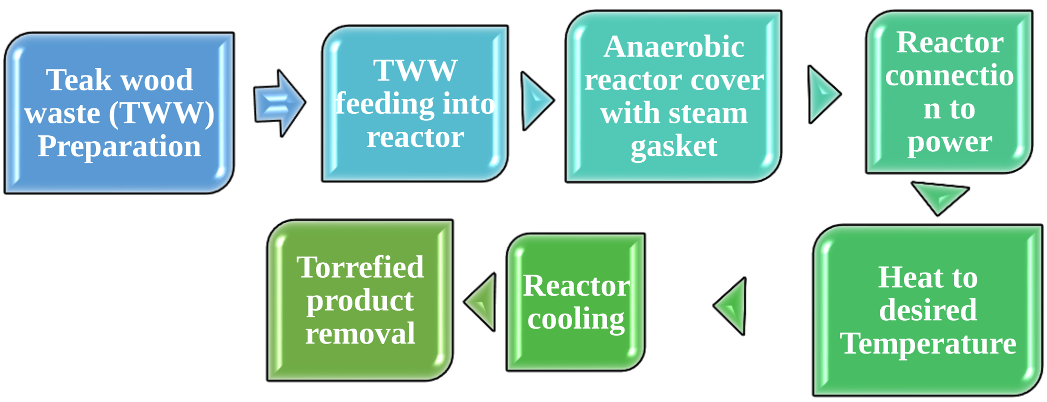

Figure 5. Experimental Flowchart

The oven was heated to 250°C for ten minutes, with a 90% mass spectral matching accuracy, after four minutes at 40°C. A calorimeter was used to measure heat in a mass of water by burning biomass samples T1-T5 for teak wood at standard conditions (0°C and 1 bar and constant pressure) for 30 minutes. The energy content of Teak wood biomass burned is calculated by dividing the resulting energy value by grams of samples T1-T5.

Equations 1 through 5 are mathematically used to determine the proportion of moisture content (M_c), volatile matter (V_m), and ash content (A_c), fixed carbon (F_c) and bulk density (B_d) in the analytical sample, respectively. The sample % elemental composition of oxygen (O), carbon (C), nitrogen (N), sulphur (S), and hydrogen (H) were computed. The percentages of mass and energy yields of torrefied teak wood samples were computed as contained in equations 6 and 7.

$$M_c = \frac{m_1 - m_2}{m_1} x\ 100 \qquad (1)$$

$$V_m = \frac{m_2 - m_3}{m_1} x\ 100 \qquad (2)$$

$$A_c = \frac{W_c - W_s}{W_s} x\ 100\% \qquad (3)$$

$$F_c = 100 - (M_c + A_c + V_m) \qquad (4)$$

$$B_d = \frac{W_{ds}}{V_c} \qquad (5)$$

$$M_y = \frac{m_t}{m_r} x\ 100 \qquad (6)$$

$$E_y = \frac{h_t}{h_r} x\ 100 \qquad (7)$$

Where; m1 is weight of specimen and m2 is weight of specimen after drying in moisture test, m3 is weight of specimen after drying in muffle furnace for 7 minutes, W_c is the weight of crucible plus sample, W_s is the weight of empty crucible, W_s is the weight of sample, W_ds is the weight of dried sample and V_c is the volume of the shape(cylinder).

3. Results and Discussion

3.1 Proximate and elemental analysis of torrefied biomass teak wood sample (TWS)

Table 1 shows that moisture, volatile matter, ash, and fixed carbon in teak wood biomass samples increase with torrefaction temperature, as observed in sample T4. The treatments of Teak wood alter its elemental composition and providing crucial insights into its heating behavior. Table 2 presents the variations in bulk density of T1-T5 wood under different treatment conditions, both before and during torrefaction procedures such as gasification, combustion, transportation, and storage. The study reveals that thermal treatment conditions significantly impact the bulk density of Teak wood, providing valuable insights into the physical changes resulting from various treatment techniques. Table 3 presents the findings of the elemental analysis of the samples T1-T5's carbon, hydrogen, oxygen, nitrogen, and sulfur composition. The outcome reveals that Teak wood's chemical structure changes with heat treatment, with higher carbon concentration enhancing energy potential. Figure 6 reveals that as torrefied temperature increases, the bulk density of torrefied biomass samples decreases, resulting in increased porosity, grindability, and energy content.

Table 1: Proximate analysis result for teak wood sample (TWS)

S/n	Sample label	M_c (%)	V_m (%)	A_c (%)	F_c (%)
T_1	Teak wood (Conditioned)	14.76	73.79	4.14	7.31
T_2	Teak (R.T.T, 350°C,1hr)	6.09	42.19	5.58	46.15
T_3	Teak (R.T.T,350°C,30mins)	4.32	31.24	7.34	57.10
T_4	Teak (R.T.T, 400°C,1hr)	6.33	24.60	6.12	62.94
T_5	Teak (R.T.T,400°C,30mins)	5.48	42.24	3.80	48.48

Table 2: Result on bulk density for Teak wood sample (TWS)

S/n	Samples	Bulk density(kg/m^3)
T_1	Teak wood (conditioned)	53.17
T_2	Teak wood (T(350 °C), R.T(1hr))	9.95
T_3	Teak wood (T(350 °C), R.T(40mins))	15.50
T_4	Teak wood (T(400 °C, R.T (1hr))	18.34
T_5	Teak wood (T(400 °C, R.T (40 mins))	14.36

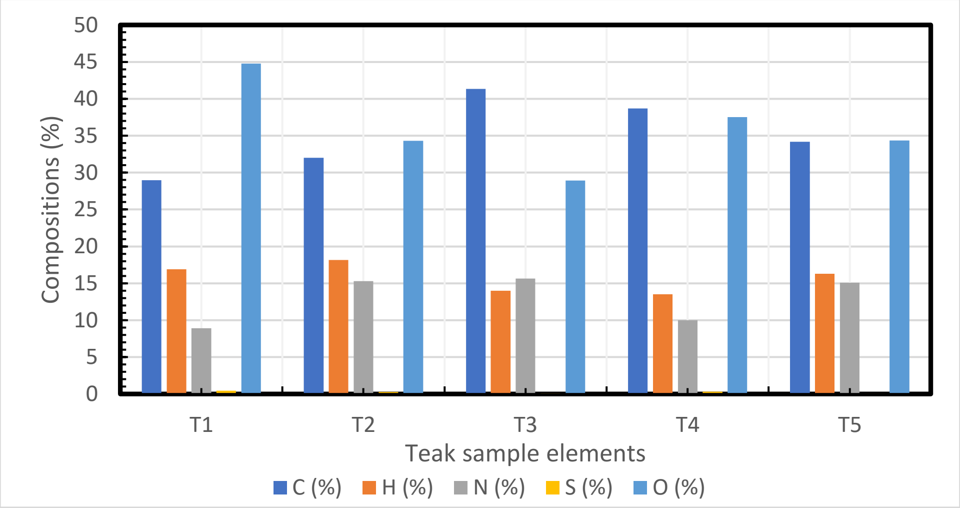

Table 6: Elemental analysis result for teak wood sample (TWS)

3.2 Effect of torrefaction treatment on mass and energy yield in biomass TWS

Table 4 presents the mass and energy output of the torrefied TWS at different residence durations and torrefaction temperatures. The mass yield decreases with rising residence period and torrefaction temperature, with energy output ranging from 60-20% of torrefied TWS at temperatures between 350-400°C. Torrefied TWS demonstrated enhanced fuel quality and combustion attributes in biomass sample T2 (from 40 to 70%) compared to non-torrefied biomass samples in conjunction with Wild and Calderon, (2021).

3.3 Effect of Torrefaction Conditions on bulk density of the biomass TWS

Table 5 shows that the bulk density of the TW biomass sample decreases as the torrefaction temperature increases, as demonstrated by sample T5 at 350°C and 1 hour resident temperature. The bulk density of all torrefied biomass samples significantly decreased with an increase in torrefied temperature compared to untreated biomass samples. The increase in porosity significantly improves the energy content and grindability of biomass.

3.4 Effect of Torrefaction treatment on calorific value of biomass TWS

Figure 7 shows energy content in torrefied biomass sample (TWS), with higher heating calorific value HCV and lower calorific value (LCV) due to torrefaction temperature condition, and increased energy content with concentration rise. The torrefied biomass sample T3 (Teak wood R.T.T. 350°C, 40 minutes) showed the highest HCV and LCV values when compared to raw biomass sample T1. The biomass sample torrefied with carbon black showed an overall increase in energy content ranging from 15% to 50% as contained in Yue et al., 2017 and Wild and Calderon, 2021). Tables 1 and 2 show constituent makeup of samples, while Table 5 shows percentages of carbon, oxygen, aluminum, silicon, iron, potassium, sulfur, and calcium contributing to torrefaction composition. The elemental composition and porous surface of samples T1-T5 indicate torrefaction-induced changes.

Table 3. Estimation of mass and energy yield of the Torrefied TW Sample

Sample		Moisture Content (%)	Heating CV (MJ/kg)	Mass yield (kg)	Energy yield (kW)
Teak wood control	T_1	12.35	12.21		
Teak wood (R.T.T 350 °C, 40mins)	T_2	5.73	17.43	0.2434	0.5641
Teak wood (R.T.T 400 °C,1hr)	T_3	3..08	18.12	0.2118	0.4986
Teak wood (R.T.T 400 °C, 40mins)	T_4	4.00	18.68	0.2103	0.4739
Teak wood (R.T.T 350 °C,1hr)	T_5	24.72	16.84	0.2435	0.6492

Table 4. Laboratory test result on bulk density for TW biomass sample

S/N	Samples	Bulk density (kg/m^3)
T_1	Teak wood (Control)	91.28
T_2	Teak wood (R.T.T, 350°C,1hr)	22.42
T_3	Teak wood (R.T.T, 350°C,30mins)	18.43
T_4	Teak wood (R.T.T, 400°C,30mins)	16.02
T_5	Teak wood (R.T.T, 400°C,1hr)	13.64

Table 5: Elemental composition of samples T_1 – T_4

Element	T_1 (%)	T_2 (%)	T_3 (%)	T_4 (%)
Carbon (C)	3.22	28.84	25.37	42.57
Oxygen (O_2)	34.86	11.89	20.45	10.73
Aluminum (Al)	0.74	0.39	0.57	0.82
Silicon (Si)	48.43	44.76	41.08	42.64
Iron (Fe)	0.54	0.86	0.68	0.78
Potassium (K)	3.56	3.34	5.52	6.54
Sulphur (S)	2.99	2.11	2.46	2.01
Calcium (ca)	0.68	1.22	1.04	1.00

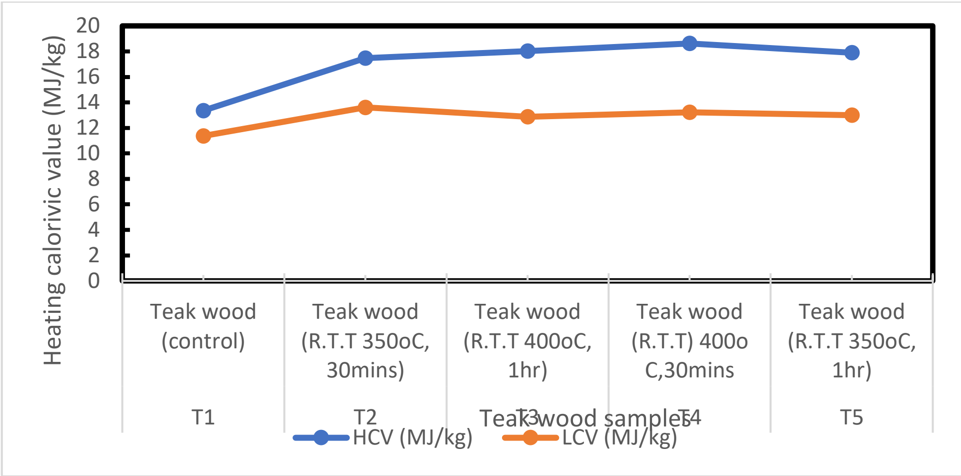

Figure 7. High and low calorific value of TW biomass

Torrefied teak wood biomass enhances economic viability, energy efficiency, and sustainability by converting waste into wealth, reducing carbon sequestration and greenhouse gas emissions, and advancing renewable energy technologies. The torrefied biomass sample's energy output exceeds mass yield, and increased torrefaction temperature and residence time increase carbon content by 15-50%.

4. Conclusion

The study utilized forestry and agriculture waste to transform teak biomass waste into energy, focusing on improving heating value factors and analyzing heat treatment impacts on the fuel's energy content at torrefaction temperature 350oC-400oC and residence time of 40 minutes to an hour. The torrefied products were collected and analysed for their compositions, contents, and characteristics. The study found that temperature and time significantly influenced the composition of teak wood, leading to higher fixed carbon, less moisture, volatile matter, and more ash. Teak wood's composition significantly influences its suitability as a biomass feedstock for electricity production, with structural changes indicating the potential for customizing wood density based on treatment parameters. Teak wood's chemical structure changes, impacting energy yield and reactivity. Thermal treatment enhances energy potential, making it practical for energy conversion operations. The research optimizes Torrefaction conditions for specific energy applications using this valuable knowledge, resulting in the following inferences:

i. It increases economic viability and energy efficiency.

ii. It converts waste into wealth and provides an alternative energy source.

iii. It lessens the possibility of carbon sequestration and greenhouse gas emissions.

iv. It advances technologies for renewable energy and advances the objectives of sustainable development.

v. The torrefied TW biomass sample's predicted energy output is more than its mass yield, resulting in the torrefied sample's energy densification.

vi. The biomass sample (TW) under consideration showed a rise in bulk density as the temperature of torrefaction rose, leading to an improvement in their energy content and grindability.

vii. The torrefied biomass sample's elemental composition showed that when the torrefaction temperature and residence time increased, the solid fuel's carbon content rose by 15-50%.

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