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Characteristics of Residence Time of the Torrefaction Process on the Result of Pruning Kesambi Waste

Jemmy Jonson Sula Dethan[1,✉], Fredrik Julius Haba Bunga[1], Mellissa Erlyn Stephanie Ledo[2], Jemseng Carles Abineno[3]

[1] Agriculture Engineering Department, Artha Wacana Christian University of Kupang, INDONESIA.

[2] Biology Department, Artha Wacana Christian University of Kupang, INDONESIA.

[3] Dryland Agriculture Management Study Program, State Agricultural Polytechnic of Kupang, INDONESIA

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Corresponding Author:
✉ johnson@ukaw.ac.id
(Jemmy Jonson Sula Dethan)

ABSTRACT

The excessive use of kesambi (Schleichera oleosa) tree to produce charcoal threatens the sustainability of kesambi plants since it takes several decades to regenerate new branches. This research aims to determine the characteristics of torrefied kesambi pruning waste. The torrefaction reactor has a diameter of 400 mm. An iron basket was positioned 100 mm above the reactor base, holding the material within an aluminum boxes. The reactor temperature was maintained at 300 °C using a K-type thermocouple sensor. A heater was placed near the reactor base and covered. The characteristics of the semi-charcoal biomass product were identified, including mass yield, water absorption capacity, moisture content (D3173, 2013); ash content (ASTM D1102-84, 2013); volatile matter (%) (ASTMD3175, 2011); and fixed carbon (%) (ASTM, 2013). The results showed as the residency time rises, the color of the torrefied kesambi pruning waste turned from brown to black. The results of torrefaction kesambi pruning waste at different residence times indicated a decrease in mass yield with an increase in residence time, with the lowest mass yield observed at a residence time of 20 min. The water absorption capacity of torrefied material was found to be in between 0.65% and 0.675%, or less than 1%; whereas higher heating value (HHV) was predicted to be 19.56 – 19.84 MJ/kg.

1. INTRODUCTION

The kesambi tree (*Schleichera oleosa*) is an important plant in the East Nusa Tenggara province, Indonesia, as the production of kesambi charcoal has long been carried out by the local community. The development of se'i meat production, a local dish renowned both nationally and internationally, has increased the utilization of kesambi stems. The utilization of kesambi begins with the roasting and smoking process of se'i, resulting in a distinct quality and flavor. Excessive use of kesambi wood may threaten the sustainability of the kesambi plant, as it takes decades for the stems to mature. This particular type of wood has a medium to high wood density containing over 40% carbon, over 30% sulfur, and over 40% cellulose, along with approximately 20% lignin (Maiti *et al*., 2016). Therefore, it is necessary to provide alternative energy. A popular heat treatment method for enhancing the properties of biomass fuel is torrefaction. Heating biomass to 200–300 °C in an oxygen-free atmosphere is the process's main step. The biomass undergoes chemical processes as a result of this treatment, producing fuel that is denser and more uniform (Tumuluru *et al*., 2021).

Because of its high lignin and cellulose content, kesambi is a common plant in Southeast Asia that can be utilized for torrefaction. Temperature and residence time must be optimized in order to produce the required fuel properties in kesambi pruning waste (leaves and twigs) during the torrefaction process. It has been discovered that torefaction works best when it is conducted at a temperature of about 275°C for 30 minutes (Martín-Pascual *et al*., 2020).

The yield and quality of the fuel that is produced can be affected by adjusting the temperature during the torrefaction process. An energy fuel with less density can be produced if the temperature is too low since the biomass's chemical reactions might not go as best they can. Biomass may burn at an excessively high temperature, resulting in fuel of inferior quality (Tang *et al*., 2022). Process optimization also takes into account residence time, or the amount of time biomass is exposed to the temperature required for torrefaction. Increased danger of burning or charring can result in lower fuel quality, while longer residence times can produce fuels with higher energy densities (Ribeiro *et al*., 2018).

Kesambi wood has a dense, hefty, and extremely hard-textured. Furthermore, it has a maximum calorific value (HHV) of 5830 cal/g (Martín-Pascual *et al*., 2020). The torrefaction method for producing materials close to charcoal for making briquettes still contains ingredients that produce the color, aroma and taste of kesambi. Thermochemical conversion is defined based on temperature, duration, and presence or absence of oxygen and based on these factors it is classified as torrefaction, pyrolysis, and gasification (Arshad, 2017). According to van der Stelt *et al*. (2011), torrefaction is a low-temperature thermal biomass conversion process that depolymerizes the majority of hemicellulose biomass components, causing the depolymerization of most hemicellulose biomass components. Low heating rates, a lengthy reactor residence time, and an oxygen-free environment are used during this treatment (Hughes & Qureshi, 2014).

Torrefied dried coconut leaves were used in Pestaño & Jose (2016) study on the physical properties and combustion of refractory and non-torrefactive biomass, greatly increasing the calorific value over untreated biomass. The residence period and torrefaction temperature have a major impact on semi-char products. Malak *et al*., (2016) found that roasting willow leaf biomass worked better than carbonization for solid biofuel briquettes. According to Rasid *et al*. (2019) higher torrefaction temperatures provide higher-energy of semi-char products with larger carbon contents and better calorific values. Through the reduction of raw biomass limits, the torrefaction process maximizes mass production and carbon as an energy source. After torrefaction treatment, stem and stump wood can be ground much more easily, requiring less energy to crush them down to 87 and 70 kWh/ton, respectively, when burned at 225°C. According to Ye *et al*., (2017), this amounts to less than half of the energy required for grinding untreated samples. The amount of energy needed to mill raw bark is far less than that of raw stem and stump wood, and the ability to mill bark wood is not greatly affected by torrefaction.

Because of cellulose binding to lignin in the biomass and hemi-cellulose degradation, the lignin concentration of TKKS pellets rises by 2.70%. Torrefaction results in an increase in ash content to 14.62%. In the meantime, the fixed carbon content rises to 65.70 percent and the volatile matter (VM) concentration rises to 79.32%, satisfying the SNI 8675:2018 requirements. Before torrefaction, empty palm fruit bunch pellets have a calorific value of 15.82 MJ/kg; following torrefaction with electric furnaces, this value increases to 18.28 MJ/kg (Rani *et al*., 2020). The amount of energy needed to mill raw bark is far less than that of raw stem and stump wood, and the ability to mill bark wood is not greatly affected by torrefaction. Compared to untreated samples, biomass samples that were dried in the ground had substantially smaller particles (Ye *et al*., 2017). Biomass is used as a sustainable alternative energy source, systems with greater capacity and shorter time periods must be developed (Saputra *et al*., 2022). In order to maximize environmental conditions with optimal usage, more study is required on torrefaction processes employing various raw materials (biomass) (Rani *et al*., 2020). This study aims to characterize the moisture content, VM content, and fixed carbon of the torrefied kesambi trimming wastes including small twigs and leaves.

2. MATERIALS AND METHODS

The research was conducted at the Artha Wacana Christian University Exact Laboratory and the Nusa Cendana University Bioscience Laboratory in November and December 2022. Trimming wastes of kesambi trees (mainly twigs and leaves) were chosen as the main source of raw material for this study. The wastes of the kesambi tree pruning were then broken into small pieces and placed in the torrefaction reactor. Digital scale Ohaus PX224, 0.3 mm Disc

Mill, Tyler sieve 10–60 mesh, thermocouple with K type sensor, and electric heater were the equipment utilized in this study. The kesambi wastes was pre-dried for about a week using the sunrise.

2.1. Torrefaction Reactor

The torrefaction process of kesambi pruning wastes was performed in a vertical reactor. The reactor had a size of 60 cm long and 40 cm in diameter (Figure 1). This reactor was able to withstand up to temperature of 600 °C. Iron baskets (diameter 36 cm, height 50 cm) was inserted and placed 100 mm above the base of the reactor to hold packed kesambi wastes. About 50 g of kesambi trimming wastes (twigs and leaves) was packed in a tightly closed aluminum box with a size of 12cm x 16 cm. Using a type K thermocouple sensor, the reactor temperature was kept at 300 °C. The heater was positioned near the reactor's base, which was covered in zinc material to transfer the heat.

2.2. Experimental Procedure

The prepared kesambi pruning were then torrefied to a temperature of 300 °C at various residence times as shown in the Table 1. In this experiment, 300°C was chosen as the torrefaction temperature because it is the highest limit for the torrefaction process. After torrefaction, the biomass from trimmed kesambi was then ground using a 0.3-mm disc mill, which was a grinding machine. Particle size distribution analysis was carried out by sieving for 720 seconds on 200 grams of powder, which had been crushed using a disc mill. The powder is sieved through six sieve sizes ranging from 10 to 60 mesh. Following that, the water absorption was determined by immersing 10 g of torrefied trimming in water for 180 minutes in an environment with an average relative humidity of 60%. To measure the change in weight of the material, the trimmed prunes were weighed every 30 minutes. A thermohygrometer was used to measure room temperature and humidity.

Figure 1. Torrefaction reactor (left), iron basket (middle), and reactor loaded with packed kesambi wastes

Table 1. Operating conditions for torrefaction of kesambi pruning wastes

Sample	Residence Times (minutes)	Temperature (°C)
A	10	300
B	15	300
C	20	300

The mass yield of torrefied kesambi pruning wastes was weighed, then calculated by the equation:

$$mass\ yield = \frac{m_{torrefied}}{m_{ffeed}}\ x\ 100\% \qquad (1)$$

where mass yield = mass product (%); $m_{torrefied}$ = mass torrefied product (gr); and m_{ffeed} =mass raw material (gr)

Proximate analysis based on the ASTM standard. Moisture measurement referred to D3173 (2013), ash referred to ASTM D1102-84 (2013), VM referred to ASTMD3175 (2011). Fixed carbon was calculated using (ASTM, 2013). Fixed carbon is the resultant of the sum of the percentages of moisture, ash and VM minus 100.

3. RESULTS AND DISCUSSION

The appearance of the pruning of kesambi at different residence times (10–20 minutes) at 300°C is presented in Figure 2. The difference in color varies with increasing residence time. As the residency time rises, the kesambi leaves and pruning turn from brown to black in hue.

Torrefactions 20 minutes　　Torrefactions 15 minutes　　Torrefactions 10 minutes

Figure 2: Kesambi Pruning Torefaction Results Physical Appearance

3.1. Mass Yield

The residence time during torrefaction of kesambi pruning wastes had a significant effect on the mass yield of torrefied product. The longer the residence time, the more organic matter in the feedstock decomposes, leading to a reduction in the overall mass of the product. This is due to the loss of volatile organic compounds and moisture from the material due to exposure to high temperatures. At lower residence times, the torrefaction process does not completely remove all the volatile compounds and water, which causes a higher mass yield. The degree of reduction in mass yield will depend on several factors, such as the initial moisture content (MC) of the material, the temperature and pressure conditions of the torrefaction process, and the composition of the twigs.

Figure 3 shows the effect of residence time on mass yield (%) from torrefaction of kesambi pruning waste. Mass yield decreases with increasing residence time. Along with the heating process, the torrefaction process will dry the feedstock and the waste lignocellulosic components will be rearranged. Mass yield can also be influenced by the ash content of the torrefaction product. As more inorganic material from the feedstock is retained in the torrefaction product, the ash content increases with longer residence times. Since ash content increases the weight of the final product without increasing its energy content, this can lead to a decrease in mass yield.

Important variables that affect how well the process works and how long it takes are the residence time and the torrefaction temperature (Ajikashile *et al*., 2023). Given that torrefaction is carried out at 200°C to 300°C and that hemicellulose and cellulose have corresponding thermal breakdown temperatures of 220°C to 315°C and 315°C to 400°C. It is well known that the operating temperature significantly affects the yield (Mościcki *et al*., 2017). Depending on the torrefaction temperature, torrefaction is categorized as mild (200°C to 235°C), mild (235°C to 275°C), or severe (275°C to 300°C).

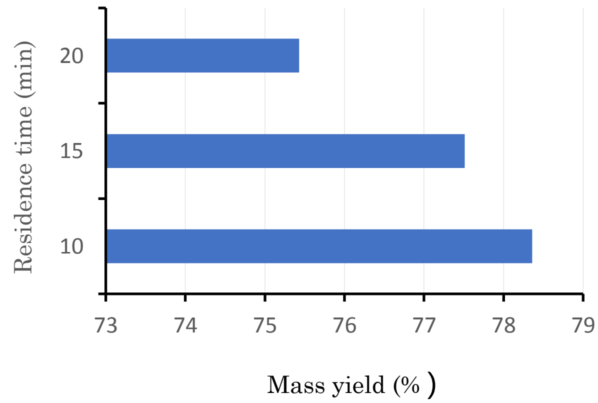

Figure 3. Effect of residence time on the mass yield (%) of pruning kesambi wood

The torrefaction treatment had these beneficial effects while keeping the energy yields (between 90 and 96%, daf) and mass yields (between 75 and 94%, daf) at acceptable levels (Jeguirim & Khiari, 2022). Longer residence times can result in a lower mass yield, but may lead to a higher energy content, as more volatile compounds are removed and the organic matter is more completely degraded. On the other hand, shorter residence times may result in a higher mass yield, but with a lower energy content as less volatile compounds and moisture are removed. The optimum residence time will depend on the desired balance between mass yield and energy content, and will likely be influenced by a number of factors, including the initial MC, temperature and pressure conditions, and the composition of the feedstock.

3.2. Water Absorption

Water absorption is a critical factor that affects the quality and performance of torrefied products, especially for applications such as fuel pellets, briquettes, and particleboards. The water absorption capacity of torrefied products directly affects their durability and combustion efficiency. The residence time determines the length of exposure of the feedstock to high temperatures, which affects the water absorption capacity of the torrefied product. The water absorption capacity of torrefied kesambi pruning wastes was found to be between 0.65% and 0.675%, or less than 1% (Figure 4). During torrefaction, water and volatile compounds in the torrefied material will be released, and lignocellulosic changes will occur in the material causing the surface of the particle material to harden so that water is difficult to enter into the material.

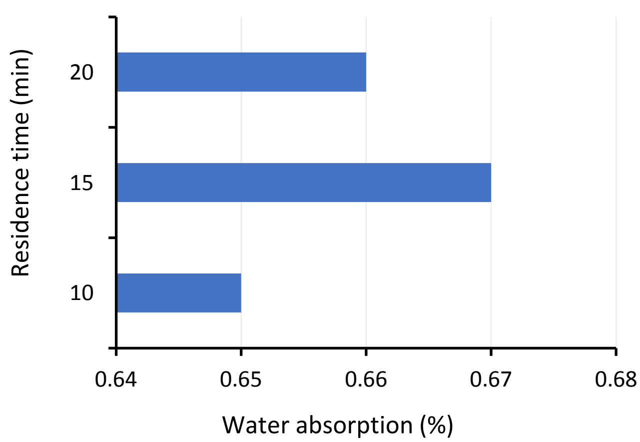

Figure 4. Effect of torrefaction residence time on water absorption from pruning waste of kesambi

Torrefaction reduces the MC of kesambi pruning wastes by eliminating the volatile organic compounds and water-soluble substances. As the residence time increases, the torrefaction process becomes more intensive, leading to further reductions in MC and an increase in the water resistance of the torrefied product. The reduction in MC of the torrefied product leads to a decrease in its water absorption capacity. This is because the water molecules cannot penetrate the surface of the torrefied product as easily as it would with untreated biomass. Additionally, the torrefaction process changes the structure of the kesambi wastes, making the cell walls denser and more compact, which further reduces the water absorption capacity. When the torrefied product is utilized as a fuel, the reduced water absorption capacity is advantageous since it lowers the possibility of spontaneous combustion and the amount of water needed for efficient combustion. However, low water absorption capacity may impair the product's performance in applications where the torrefied material is utilized as a composite material, including particleboards and briquettes, making it less appropriate for these uses.

The water absorption capacity of the torrefied product can be optimized by controlling the residence time of the torrefaction process. A moderate residence time can result in a torrefied product with an optimal balance between low water absorption capacity and adequate durability. An increase in the residence time leads to a decrease in the water absorption capacity, while a decrease in the residence time leads to an increase in the water absorption capacity.

3.3. Particle Fraction of Torrefied Product

Based on the changes taking place during torrefaction process, the residence time affect the powder fraction in the torrefied product. Figure 5 shows the percentage of the particle size fraction resulting from the torrefied of kesambi trimming wastes at different residence time. Figure 5 shows that the longer the residence time results in fewer large particles measuring 20 mesh. On the other hand, small particles measuring 60 mesh or smaller increase in number as the residence time increases. Particles with a size of 40 mesh are almost the same and are not affected by the residence time of the torrefaction process. As the residence time increases, the biomass material is exposed to hot atmosphere for a longer period. This leads to increased degradation of the cell walls and lignocellulosic components, causing the material to become more brittle and prone to breakage. This increased brittleness can result in a larger proportion of the torrefied product being in the form of smaller particles or even a powder.

In addition to the torrefaction residence time, additional variables that affect the ultimate particle size of the torrefied product include the raw material's initial particle size, the torrefaction temperature, and the presence of moisture during the process. The existence of the powder fraction may have an impact on these additional parameters as well as the torrefied product's yield. The powder fraction will rise with an increase in the torrefaction residence time. To completely comprehend the connection between the torrefaction residence time, the torrefied product's particle size, and the process yield, more investigation is necessary.

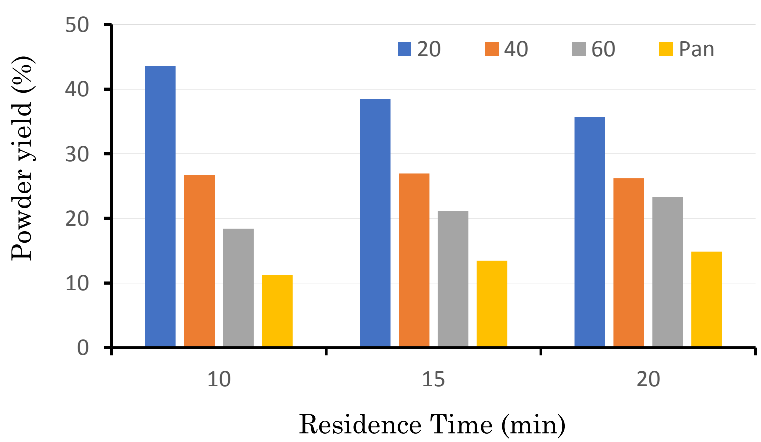

Figure 5. Effect of residence time on fraction of particle size of torrefied kesambi wastes. (Note: 20, 40, 60, are sieve sizes expressed in mesh units, the larger the number means the smaller the particle size. Pan is a sieve container without holes at the bottom of the sieve arrangement).

3.4. Proximate Analysis

3.4.1. Moisture Content (MC)

The torrefaction process reduces the MC and increases the calorific value of sawdust (Mohamed *et al*., 2019). The water content of torrefied kesambi pruning is an important factor that can influence the quality and suitability of the torrefied product for various applications. Torrefaction residence time can have a significant influence on the water content of the resulting torrefaction product. The longer the residence time, the longer the feedstock is exposed to a hot environment, causing more water to be released from the kesambi pruning waste. This results in reduced water content in the torrefaction product, making it more suitable for use as fuel. Table 2 shows that the lowest water content was produced in treatment C (torrefaction residence time 20 minutes) with a water content of 4.56% and was significantly lower than the water content of the torrefaction product with a residence time of 10 minutes.

The water content of biomass torrefaction decreases as the process progresses. However, it should be remembered that prolonged torrefaction can cause chemical damage to the biomass, thereby reducing product quality. To maintain good product quality, the torrefaction period must be precisely controlled. Loss of water from biomass during the torrefaction process may have a negative impact on the fuel quality of the torrefaction product. Too long a residence time can result in the torrefaction product becoming too dry, which will reduce fuel stability, energy density, quality, and storage capability. The water content of torrefaction results can also be influenced by the initial feedstock water content. Higher water content in torrefaction products can be caused by the inability of the torrefaction process to completely remove water if the initial water content is too high.

It is important to control the residence time of torrefaction at high temperatures as well as other process variables such as temperature, heating rate, and biomass properties to obtain the ideal MC for the torrefaction product. Torrefaction products with appropriate water content, energy density and fuel quality can be produced with the help of careful control of these factors. In order for the torrefaction results of kesambi tree pruning waste to have appropriate fuel quality and energy density, the water content must be carefully controlled and optimized. This parameter is influenced by initial drying and torrefaction residence time.

Table 2. Proximate Torrefaction of Pruning Kesambi trees

Sample	Water Content	Volatile Matter	Ash	Fixed Carbon
A	5.62±0.40[a]	18.70±0.20 [a]	2.08±0.10 [a]	73.59±0.23[a]
B	5.36±0.13[ab]	23.21±0.17[b]	2.42±0.27[ab]	71.58±0.61[a]
C	4.56±0.73[b]	24.95±0.13[c]	2.90±0.23[b]	71.29±0.27[a]

Note: Numbers followed by different lowercases mean significant according to LSD test at α = 0.05.

The MC of various biomass types varies based on process condition. For instance, lodgepole pine's MC decreases with increasing temperature and torrefaction time. Tumuluru (2016) found a MC of 1.15% at a temperature of 270 °C for 120 minutes. Torrefied palm kernel shells have a MC range of 3-4% (Susanty *et al*., 2018), while corn straw torrefied using microwave has a MC of 2-2.5% (wb). Optimal torrefaction treatment of peanut shells at 300°C for 60 minutes resulted in a MC of 3.092% (Wibowo & Lestari, 2019).

3.4.2. Ash Content

Ash is a non-combustible fraction of biomass consisting of inorganic minerals such as silica, alumina and potassium. The ash content of torrefaction products is influenced by the length of torrefaction time. The longer the torrefaction time, the more chemical degradation action that occurs in the biomass, thereby increasing the ash content. Table 2 shows that the ash content increases significantly with increasing torrefaction residence time. High ash content in biomass reduces its quality as fuel. Therefore, it is important to control the length of torrefaction time precisely so that the quality of the resulting product remains high. In general, the ash content in this study is considered good for fuel because it is less than 5%.

Torrefaction at a temperature of 300°C will evaporate water and volatile contents. Because ash is an inert component, the torrefaction process will increase the ash content. The ash content of various food waste biomass varies depending on the type of waste biomass and can range from 0.86% to 22.39% (Dyjakon *et al*., 2019). Ash content may be related to mass yield. Low mass yields sometimes result in higher ash concentrations in the fuel. This is most likely caused by the relatively greater loss of organic material. This is usually caused by a stay that is too long.

3.4.3. Volatile Matter (VM)

One important component that can influence the energy density and combustion properties of torrefaction products is the volatile matter (VM) content. Table 2 shows that the fraction of VM in the final product of torrefaction is greatly influenced by the residence time of torrefaction. Duncan's test showed that the highest VM content was produced in the torrefaction residence time of 20 min (treatment C) with a VM content of 24.956%. VMs are simple fractions produced when carbon, hydrogen, oxygen, and nitrogen in organic materials are burned. VM consists of gases and liquids produced during the torrefaction process, which are formed from the chemical degradation of organic materials.

The VM content of torrefaction products may also be influenced by the initial VM content of kesambi pruning waste. If the initial VM content is too high, the torrefaction process may not effectively remove all VMs, resulting in a higher VM content in the torrefaction product.

During the torrefaction process, depolymerization of biopolymers (such as cellulose, hemicellulose, and lignin) and long polysaccharide chains occurs, resulting in the formation of a dense, hydrophobic, dry, blackened product known as torrefaction biomass or bio-coal with significantly increased energy density and grindability (Al-Haj Ibrahim, 2020). Torrefaction of bamboo produces a VM content in the range of 17–24%, while bound carbon increases to 73–76% after torrefaction (Wu & Lin, 2012). The VM content of torrefaction biomass typically ranges from 40% to 85% by weight (Chen *et al*., 2015).

3.4.4. Fixed Carbon

The fixed carbon (FC) content in torrefaction products is an important factor that can influence the energy density and combustion characteristics. Torrefaction residence time affects the FC content of the resulting torrefaction product. One explanation that the torrefaction residence time can have an impact on the FC content is the removal of VM from organic compounds in biomass during the torrefaction process. FC is the non-combustible fraction of the feedstock consisting of organic matter, ash, and inorganic minerals bound to carbon. FC is the main component of biochar produced during the torrefaction process.

The FC content of kesambi pruning waste produced from the torrefaction process is influenced by the residence time of the torrefaction. The longer the torrefaction process takes, the more chemical degradation will occur in the organic material, thereby reducing the FC content. Duranay & Akkuş (2021) stated that the quality of WVS (waste vine shoots) fuel can be improved by torrefaction at a temperature of 280 °C. After torrefaction for 60 minutes, the WVS calorific value increased from 17.8 to 24.4 MJ/kg. The FC content of WVS torrefaction products also increases, and under extreme torrefaction conditions, the atomic ratios of O/C and H/C approach the peat and lignin zones in the Van Krevelen diagram (Duranay & Akkuş, 2021). Setyawan *et al*. (2018) reported that FC content rose while the VM gradually declined as the torrefaction temperature and residence duration increased. Torrefaction at a temperature of 300°C for a sufficiently long time (15–20 min) can cause the material to become charcoal. At high temperatures, the organic components in the material undergo rapid thermal decomposition, involving the breakdown of complex structures such as cellulose, hemicellulose, and lignin into simpler compounds, resulting in significant chemical changes and producing charcoal as a residue. The results of our study, however, showed that within a torrefaction residence time of 10 - 20 minutes, the FC content was not statistically different. The FC content of torrefied kesambi pruning wastes was 71.29-73.59%.

Compared with fresh biomass, torrefaction biomass is proven to have better attributes such as lower water content, higher FC content, and higher heating value. The greater carbon and less oxygen content indicate that torrefaction can improve fuel characteristics (Phuang *et al*., 2021). Increasing the residence time causes the loss of a large number of VM organic compounds from kesambi tree pruning waste. This can increase the FC content in the torrefaction product, thereby increasing the energy density and improving the fuel characteristics.

3.4.5. HHV of the Torrefied Product

Using the data in Table 1 and Table 2, a higher heating value (HHV) was predicted using three empiric formulas. Equation (2) from Parikh *et al*. (2005) and Equation (3) from Nhuchhen & Salam (2012) predict HHV based on FC, VM, and Ash content. Whereas Equation (4) (Wahid *et al*. (2017) involves two more parameters to calculate HHV Equation, namely torrefaction temperature (T) and residence time (t).

$$HHV = 0.3536\ FC + 0.1559\ VM - 0.0078\ Ash \tag{2}$$

$$HHV = 19.288 - 0.2135\ (VM/FC) - 1.9584\ (A/VM) + 0.0234\ (FC/A) \tag{3}$$

$$HHV = 15.8514 + 1.9293(FC/VM) + 0.0418(VM/ASH) + 0.1398(ASH/FC) + 0.0234t + 0.0082T \tag{4}$$

The results of the HHV prediction analysis are presented in Table 3. The torrefaction process causes the decomposition and dehydration of organic compounds in biomass (van der Stelt *et al*., 2011). The longer the process takes, the more organic compounds can decompose, increasing the carbon concentration and potential energy in the torrefaction product. At temperatures ranging from 200 to 300°C, the thermal decomposition of biomass became apparent, resulting in a substantial 19 wt% weight loss. This notable reduction in weight is attributed to the thermal degradation and devolatilization processes of biomass, during which certain volatile components in bamboo are emitted (Chen *et al*., 2021). The torrefaction process generally reduces the water content in biomass. The results showed that HHV of torrefied kesambi wastes are almost same for three different residence time. The three models resulted different HHV values of the torrefied kesambi wastes. Prediction using formula from Parikh *et al*. (2005) the highest values of around 29 MJ/kg, followed by model from Wahid *et al*. (2017) with HHV values of ± 25 MJ/kg, and close to 20 MJ/kg by using model from Nhuchhen & Salam (2012). As a comparison, oil palm empty fruit bunch (OPEFB) pellets torrefied 280 °C and a duration of 20 min had HHV of 18.28 MJ/kg (Rani et al., 2020). Similar HHV values of 19.70 – 21.09 MJ/kg was reported for oil palm shell torrefied at 240 – 280 °C for 30 – 60 min (Abnisa *et al*., 2011). Other oil palm wastes torrefied at 240 – 300 °C for 30 – 60 min were reported to have HHV of 19.82 – 23.79 in MJ/kg for frond, 18.05 – 23.40 MJ/kg for mesocarp fiber, and 15.59 – 19.60 MJ/kg for empty bunch (Wahid *et al*. (2017). Therefore, HHV value of 19.56 – 19.84 MJ/kg calculated using model from Nhuchhen & Salam (2012) is more reasonable.

Table 3. HHV prediction of torrefied kesambi pruning waste

Sample	$HHV_{prediction}$ (MJ/kg)		
	Parikh *et al*. (2005)	Nhuchhen & Salam (2012)	Wahid *et al*. (2017)
A	28.92	19.84	26.52
B	28.91	19.71	25.02
C	29.08	19.56	24.66

The processes of briquetting and torrefaction led to an elevation in the bulk density of biomass and the valuable calorific value, respectively. As a result, the energy density of the briquettes manufactured from torrefied raw material under high pressure was enhanced (Portilho *et al*., 2020). The torrefaction process can change the chemical composition of biomass. Increasing the torrefaction time may produce a product that is richer in compounds and provides a higher heating value. Solid fuels maintain approximately 90% of their initial energy content, signifying that torrefied biomass exhibits a 10% to 20% increase in higher heating value (HHV) compared to untreated biomass. Subsequently, the solid biomass can undergo processing into pellets or briquettes (Ivanovski *et al*., 2023). Torrefaction requires lower temperatures and less energy with significantly greater yields (94%) as opposed to 33% with carbonization. Torrefied biomass has 90% of the initial energy and has 70% of efficiency, whereas the carbonization process results in efficiency of 40% with energy value 80% of the the initial biomass (Malak *et al*., 2016).

4. CONCLUSION

As the residency time rises, the kesambi leaves and pruning turn from brown to black in hue. The torrefied kesambi pruning wastes at various torrefaction residence times demonstrates that the yield percentage drops with increasing residence time, reaching its minimum weight percentage at a residence time of 20 minutes. The water absorption capacity of torrefied kesambi pruning was found to be between 0.65% and 0.675%, or less than 1% and HHV prediction 19.56 – 19.84 MJ/kg.

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REFERENCES

Abnisa, F., Daud, W.M.A.W., Husin, W.N.W., & Sahu, J.N. (2011). Utilization possibilities of palm shell as a source of biomass energy in Malaysia by producing bio-oil in pyrolysis process. *Biomass and Bioenergy*, ***35***(5), 1863-1872. https://doi.org/10.1016/j.biombioe.2011.01.033

Ajikashile, J.O., Alhnidi, M.J., Bishir, M., & Kruse, A. (2023). The influence of torrefaction temperature and reaction time on the properties of torrefied sun-dried millet and sorghum straws from the arid and semi-arid zones of Western Africa. *Biofuels, Bioproducts and Biorefining*, ***17***(3), 751–767. https://doi.org/10.1002/BBB.2464

Al-Haj Ibrahim, H. (2020). Introductory chapter: Pyrolysis. In *Recent Advances in Pyrolysis*. (Editor: H. Al-Haj Ibrahim), IntechOpen. https://doi.org/10.5772/intechopen.90366

Arshad, M. (2017). Clean and Sustainable Energy Technologies. Clean Energy for Sustainable Development: *Comparisons and Contrasts of New Approaches*, **73–89**. https://doi.org/10.1016/B978-0-12-805423-9.00003-X

ASTM. (2013). 3172-13 Standard Practice for Proximate Analysis of Coal and Coke. *ASTM International*, **13**(Reapproved).

ASTM (2013). ASTM D1102-84. Standard Test Method for Ash in Wood, *ASTM International*

ASTMD3175. (2011). Standard test method for volatile matter in the analysis sample of coal and coke. *ASTM International.*

Chen, W.H., Lin, B.J., Lin, Y.Y., Chu, Y.S., Ubando, A.T., Show, P.L., Ong, H.C., Chang, J.S., Ho, S.H., Culaba, A.B., Pétrissans, A., & Pétrissans, M. (2021). Progress in biomass torrefaction: Principles, applications and challenges. *Progress in Energy and Combustion Science*, ***82***, 100887. https://doi.org/10.1016/J.PECS.2020.100887

Chen, W.H., Peng, J., & Bi, X.T. (2015). A state of the art review of biomass torrefaction, densification and applications. *Renew. Sustain. Energy Rev*. ***44***, 847–866. https://doi.org/10.1016/j.rser.2014.12.039

D3173, A. (2013). ASTM D3173. Statistics, 03 (February 2008).

Duranay, N.D., & Akkuş, G. (2021). Solid fuel production with torrefaction from vineyard pruning waste. *Biomass Conversion and Biorefinery*, ***11***(6), 2335–2346. https://doi.org/10.1007/S13399-019-00496-0/METRICS

Dyjakon, A., Noszczyk, T., & Smędzik, M. (2019). The influence of torrefaction temperature on hydrophobic properties of waste biomass from food processing. *Energies*, ***12***(24), 4609. https://doi.org/10.3390/en12244609

Hughes, S.R., & Qureshi, N. (2014). Biomass for biorefining: Resources, allocation, utilization, and policies. *Integrated Biochemical Processes for Liquid Biofuels*, **37–58**. https://doi.org/10.1016/B978-0-444-59498-3.00002-6

Ivanovski, M., Petrovič, A., Goričanec, D., Urbancl, D., & Simonič, M. (2023). Exploring the properties of the torrefaction process and its prospective in treating lignocellulosic material. *Energies*. ***16***(18), 6521. https://doi.org/10.3390/en16186521

Jeguirim, M., & Khiari, B. (2022). Thermochemical conversion of tomato wastes. In *Tomato Processing by-Products*: *Sustainable Applications*. Elsevier, Amsterdam: 285–332. https://doi.org/10.1016/B978-0-12-822866-1.00008-9

Maiti, R., Gonzalez Rodriguez, H., & Kumari, A. (2016). Wood density of ten native trees and shrubs and its possible relation with a few wood chemical compositions. *American Journal of Plant Sciences*, **07**, 1192-1197. https://doi.org/10.4236/ajps.2016.78114

Malak, K., De La Seiglière, C., Fernández, C., Swaminathan, M., Sebastián, A., & Arora, D. (2016). Green coal: A new energy source from leaves. *Energy Procedia*, ***100***, 484–491. https://doi.org/10.1016/j.egypro.2016.10.207

Martín-Pascual, J., Jódar, J., Rodríguez, M.L., & Zamorano, M. (2020). Determination of the optimal operative conditions for the torrefaction of olive waste biomass. *Sustainability*, ***12***(16), 6411. https://doi.org/10.3390/SU12166411

Mohamed, A.R., Nadhirah, N., Nordin, A., Hasyierah, N., & Salleh, M. (2019). Chemical properties of torrefied and raw sawdust. *Journal of Advanced Research in Engineering Knowledge*, ***6***, 7–14. www.akademiabaru.com/arek.html

Mościcki, K.J., Niedźwiecki, Ł., Owczarek, P., & Wnukowski, M. (2017). Commoditization of wet and high ash biomass: Wet torrefaction. *Journal of Power Technologies*, ***97***(4), 354–369.

Nhuchhen, D.R., & Salam, P.A. (2012). Estimation of higher heating value of biomass from proximate analysis: A new approach. *Fuel*, ***99***, 55–63. http://dx.doi.org/10.1016/j.fuel.2012.04.015

Parikh, J., Channiwala, S.A., & Ghosal, G.K. (2005). A correlation for calculating hhv from proximate analysis of solid fuels. *Fuel*, **84**(5). https://doi.org/10.1016/j.fuel.2004.10.010

Pestaño, L.D.B., & Jose, W.I. (2016). Production of solid fuel by torrefaction using coconut leaves as renewable biomass. *International Journal of Renewable Energy Development*, ***5***(3), 187-197. https://doi.org/10.14710/ijred.5.3.187-197

Phuang, Y.W., Ng, W.Z., Khaw, S.S., Yap, Y.Y., Gan, S., Lee, L.Y., & Thangalazhy-Gopakumar, S. (2021). Wet torrefaction pre-treatment of yard waste to improve the fuel properties. *Materials Science for Energy Technologies*, ***4***, 211–223. https://doi.org/10.1016/J.MSET.2021.06.005

Portilho, G.R., de Castro, V.R., Carneiro, A. de C.O., Zanuncio, J.C., Zanuncio, A.J.V., Surdi, P.G., Gominho, J., & Araújo, S. de O. (2020). Potential of briquette produced with torrefied agroforestry biomass to generate energy. *Forests*, ***11***(12), 1–10. https://doi.org/10.3390/f11121272

Rani, I.T., Hidayat, W., Febryano, I.G., Iryani, D.A., Haryanto, A., & Hasanudin, U. (2020). Pengaruh Torefaksi terhadap Sifat Kimia Pelet Tandan Kosong Kelapa Sawit. Jurnal Teknik Pertanian Lampung. *Journal of Agricultural Engineering*, ***9***(1), 63–70. https://doi.org/10.23960/jtep-l.v9.i1.63-70

Rasid, R. A., Chin, T. M., Ismail, M., & Rahman, R.N.U.A. (2019). Effect of Torrefaction Temperature, Residence Time and Particle Size on the Properties of Torrefied Food Waste. *Indonesian Journal of Chemistry*, **19**(3) :753–760. https://doi.org/10.22146/ijc.39718

Ribeiro, J.M.C., Godina, R., Matias, J.C. de O., & Nunes, L.J.R. (2018). Future perspectives of biomass torrefaction: Review of the current state-of-the-art and research development. *Sustainability*, ***10***(7), 2323. https://doi.org/10.3390/su10072323

Saputra, B., Gracia, K., Tambunan, A., Suri, I.F., Febryano, I.G., Iswandaru, D., & Hidayat, W. (2022). Effects of torrefaction temperature on the characteristics of betung (*Dendrocalamus asper*) bamboo pellets. *Jurnal Teknik Pertanian Lampung*, ***11***(2), 339–353. https://doi.org/10.23960/jtep-l.v11i2.339-353

Setyawan, D., Yoo, J., Kim, S., Choi, H., Rhim, Y., Lim, J., Lee, S., & Chun, D.H. (2018). Torrefaction effect on the grindability properties of several torrefied biomasses. *Korean Chemical Engineering Research*, ***56***(4), 547–554. https://doi.org/10.9713/KCER.2018.56.4.547

Susanty, W., Helwani, Z., & Zulfansyah. (2018). Torrefaction of oil palm frond: the effect of process condition to calorific value and proximate analysis. *IOP Conf. Ser.: Mater. Sci. Eng.*, ***345***, 12016. https://doi.org/10.1088/1757-899X/345/1/012016

Tang, Y., Dong, J., Zhao, Y., Li, G., Chi, Y., Weiss-Hortala, E., Nzihou, A., Luo, G., & Ye, C. (2022). Hydrogen-rich and clean fuel gas production from co-pyrolysis of biomass and plastic blends with CaO additive. *ACS Omega*, ***7***(41), . https://doi.org/10.1021/acsomega.2c04279

Tumuluru, J.S. (2016). Effect of deep drying and torrefaction temperature on proximate, ultimate composition, and heating value of 2-mm lodgepole pine (*Pinus contorta*) grind. *Bioengineering*, ***3***(2). https://doi.org/10.3390/bioengineering3020016

Tumuluru, J.S., Ghiasi, B., Soelberg, N.R., & Sokhansanj, S. (2021). Biomass torrefaction process, product properties, reactor types, and moving bed reactor design concepts. *Frontiers in Energy Research*, **9**, 462. https://doi.org/10.3389/FENRG.2021.728140/BIBTEX

van der Stelt, M.J.C., Gerhauser, H., Kiel, J. H.A., & Ptasinski, K.J. (2011). Biomass upgrading by torrefaction for the production of biofuels: a review. *In Biomass and Bioenergy* (Vol. ***35***, Issue 9). https://doi.org/10.1016/j.biombioe.2011.06.023

Wahid, F.R.A.A., Saleh, S., & Samad, N.A.F.A. (2017). Estimation of higher heating value of torrefied palm oil wastes from proximate analysis. *Energy Procedia*, ***138***, 307–312. https://doi.org/10.1016/j.egypro.2017.10.102

Wibowo, S., & Lestari, N. (2019). Effect of peanut shell torrefaction on qualities of the produced bio-pellet. *Reaktor*, ***18***(04), 183–193. https://doi.org/10.14710/REAKTOR.18.04.183-193

Wu, C.-T., & Lin, -Far-Ching. (n.d.). (2012) The properties of torrefied biomass from six major bamboos in Taiwan. *Proceedings of the 55th International Convention of Society of Wood Science and Technology.*

Ye, Y., Liu, K., Wang, Y., & Lu, P. (2017). Study on the torrefaction characteristics of raw and pelletized biomass. *11th Asia-Pacific Conference on Combustion, ASPACC 2017*.