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Research Article

Evaluating the role of operating temperature and residence time in the torrefaction of betel nutshells for solid fuel production

Pongpathai Kitrungloadjanaporn[a], Le Quang Sang[b,c], Jirasak Pukdum[d], Tinnapob Phengpom[a*]

[a] *Institute for innovative learning, Mahidol University, 999 Phuttamonthon 4 Road, Salaya, Phutthamonthon, Nakhon Pathom, 73170, Thailand*

[b] *Institute of Energy Science, Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet, Cau Giay, Ha Noi, 10072, Vietnam*

[c] *Graduate University of Science and Technology, Vietnam Academy of Science and Technology, 18 Hoang Quoc Viet, Cau Giay, Ha Noi, 10072, Vietnam*

[d] *Faculty of Architecture and Design, Rajamangala University of Technology Rattanakosin, 96 Phutthamonthon Sai 5 Road, Salaya, Phutthamonthon, Nakhon Pathom, 73170, Thailand*

Abstract. This research addresses the urgent need for sustainable bioenergy alternatives, specifically evaluating betel nutshells as potential replacements for conventional biomass materials like coconut and palm fibers. The objective of the study was to gauge the inherent bioenergy potential of betel nutshells through an investigation of torrefaction under varying conditions, specifically temperatures ranging from 200-300 °C and residence times between 20-60 minutes in an inert environment. In this study, proximate analyses were utilized to investigate essential characteristics including moisture content, volatile matter, ash content, and fixed carbon, while a bomb calorimeter was used to determine their higher heating values. Initial results indicated that untreated betel nutshells had higher heating values and compositional similarities to coconut and palm fibers, highlighting their potential as a bioenergy source. Advanced torrefaction processes, involving increased temperatures and extended residence times, raised the fixed carbon content and reduced moisture in betel nutshells, thereby optimizing their higher heating value. This improvement is attributed to the decomposition of covalent bonds in the biomass structures, leading to the release of volatile compounds and consequent reductions in both oxygen-to-carbon and hydrogen-to-carbon ratios. Remarkably, at an operating temperature of 300 °C and a residence time of 60 minutes, torrefied betel nutshells reached a higher heating value of 25.20 MJ/kg, marking a substantial 31.39 % increase compared to untreated specimens. This study conclusively positions betel nutshells, typically considered agricultural waste, as competitive alternatives to traditional biomass resources in the biofuel industry.

Keywords: Torrefaction; Torrefied biomass; Betel Nutshells; Higher heating value; Biomass composition

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1. Introduction

The potential of agricultural byproducts as biomass feedstocks has been recognized, with a significant proportion suitable for biofuel production (Di *et al.*,1997). Specifically, Thailand's diverse agricultural landscape yields an array of residues. These residues present opportunities for conversion into transportation fuels, thermal energy, and electricity (Hoogwijk *et al.*, 2005). Nevertheless, these biomass feedstocks often have a lightweight and porous structure and retain a lot of moisture (Prins *et al.*, 2006). This characteristic diminishes their energy density, reducing their value (Zych *et al.*, 2008). The torrefaction process emerged as a promising solution to these challenges. This technique was initially explored in France in the 1930s, focusing on the effects of temperature, the rate of heating, and duration (Tańczuk *et al.*, 2009). By the 1980s, researchers, Bourgois and Doat, delved deeper, experimenting with different types of wood and varying torrefaction temperatures. Their pioneering work culminated in the creation of a prototype torrefaction facility towards the end of the 1980s. Torrefied biomass gained attention for its enriched energy content and its resilience to both water and biodegradation (Demirbas *et al.*, 2009). As a result, the advantages of torrefaction in refining the properties of raw biomass have gained momentum, especially in regions like Europe and North America (Ojolo *et al.*, 2012).

Delving into the technicalities of torrefaction, the process pivots on the thermal degradation of untreated biomass. It's typically executed at temperatures between 200 °C to 300 °C and comprises four core phases: initial heating, drying, intermediate heating leading to torrefaction, and finally, cooling. Initially, the raw biomass is heated to elevate its temperature before proceeding to the drying step. A heating rate of less than 50 °C/min is recommended for this phase. Once the biomass attains the desired temperature, usually between 90 °C and 105 °C, the drying process begins. This step ensures the evaporation of free water from the biomass, reducing its moisture content. It is crucial to remove water from the biomass, as excessive moisture or steam in the reactor can hinder the thermal degradation of the biomass during torrefaction. After drying, the biomass is further heated to the torrefaction temperature, a step known as intermediate heating. During the torrefaction phase, the biomass temperature remains consistent within the 200 °C to 300 °C range, contingent upon the specific type of biomass. During the thermal degradation phase, hemicelluloses in the

* Corresponding author
Email: tinnapob.phe@mahidol.ac.th (T. Phengphom)

raw biomass typically break down first within the temperature range of 200 °C to 250 °C. This is followed by the decomposition of lignin and a portion of cellulose between 270 °C to 300 °C. These changes alter the composition of the biomass due to thermal degradation (Chen *et al.*, 2013). Once the torrefaction process is complete, the torrefied biomass achieves a high temperature and can readily react with oxygen. Therefore, it's crucial to cool the torrefied biomass promptly to prevent the risk of spontaneous combustion. Torrefaction reactors can be categorized into three types: laboratory, pilot, and commercial scales. Laboratory-scale reactors have a production capacity of less than 20 kg/hr. In contrast, pilot-scale reactors manage 20-600 kg/hr, and commercial-scale reactors handle over 600 kg/hr.

A significant portion of the studies focuses on the laboratory level. The torrefaction reactor, when first developed at this scale in the 1930s, aimed to understand the elements affecting the torrefaction procedure. These initial laboratory investigations laid the foundation for creating a pilot-scale torrefaction reactor. Three primary varieties of laboratory-scale torrefaction reactors exist: Fixed bed, Microwave, and Fluidized bed torrefaction reactors.

In the fast-advancing domain of biomass torrefaction, various reactor designs have been developed, each providing its unique benefits. Prominently, the fixed bed torrefaction reactor stands out due to its simplistic structure. In this design, a designated amount of raw biomass is heated, facilitated by an electric heater surrounding the reactor's exterior. Research by Chen *et al.* (2015) demonstrated its effectiveness, producing torrefied cotton stalks and wheat straw that exhibited increased energy density and improved grindability. Remarkably, this modified biomass showcased distinct water-repellent characteristics. Further enhancing this narrative, Tumuluru *et al.* (2015) highlighted the value of torrefying corn stover, showing an enhanced energy density after treatment and a weight reduction reaching 45%. Shifting focus to other biomass sources, Liu *et al.* (2018) compared the combustion qualities of torrefied bamboo to lignite and coal. Concurrently, Nyakuma *et al.* (2020) explored oil palm waste and the grinding qualities of torrefied crops like willow and miscanthus.

Simultaneous advancements in the microwave torrefaction reactor realm utilize high-frequency electromagnetic waves to stimulate water molecules inside the biomass, raising its temperature. Abelha *et al.* (2020) took the lead in this direction, proposing an ideal power setting between 250-300 °C for the torrefaction of rice husk and sugarcane byproducts. Their pioneering methods achieved a 26 % boost in the heating value of rice husk and a significant 57 % increase for sugarcane residues.

The fluidized bed reactor, another significant player, functions with raw biomass situated atop a grate, accompanied by a rising warm inert gas. When optimally adjusted, this gas induces the biomass to exhibit fluid-like movement, ensuring uniform heat conditions optimal for torrefaction. An innovative investigation by Luo *et al.* (2023) employed this reactor for sawdust torrefaction using nitrogen as the inert medium. Their findings indicated that heightened torrefaction stages improved the heating value of the end product, albeit with a decrease in energy yield, as supported by Yang *et al.* (2022).

In this study, the potential of agricultural biomass, specifically from plants in the palm family, was investigated as an alternative source of solid fuel energy. The biomass included betel nutshells, palm fiber, and coconut fiber. Previous to the experimental procedure, the biomass underwent a pretreatment process. The experiment was designed to assess key variables in the biomass, focusing on its proximate analysis and higher heating value within an operating temperature of 200 to 300 °C over a duration of 20 to 60 minutes. The aim was to elucidate its potential energy yield.

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2. Materials and methods

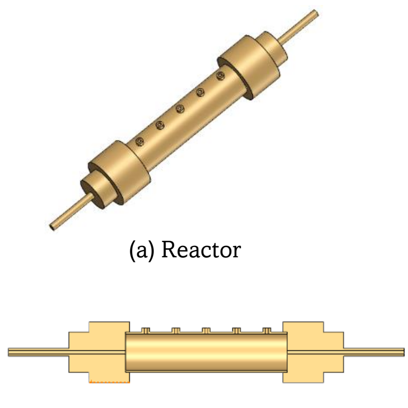
2.1 Biomass samples

In the current investigation, the potential of locally-sourced agricultural residues as a sustainable energy were examined. Specifically, the energy attributes of betel nutshells were evaluated as a candidate for solid biofuel and compared with the energy content inherent in fibers derived from palm and coconut, both taxonomically categorized within the palm family (Hoogwijk *et al.*, 2005). The distribution of particle sizes within these crushed samples was ascertained using sieve analysis, in strict compliance with the ASTM E11 standards. After grinding, the biomass samples underwent a drying process in a hot air oven (Binder redLINE RE 53), maintained at 105 °C for a span of 24 hours, and subsequently allowed to reach ambient conditions within desiccators. The post-drying mass of the samples was meticulously recorded using a high-precision digital balance, aiming for a consistent moisture content of approximately 9 ± 1%.

The prepared sample was divided into two parts: the first portion (20g) was utilized to monitor the weight loss curve and for proximate analysis, while the second portion (20g) was set apart for evaluation using a bomb calorimeter to ascertain its calorific value or higher heating value.

2.2 Experimental procedure

A batch reactor for torrefaction was designed and assembled at a laboratory scale. The apparatus for biomass pyrolysis reactor is illustrated in Figure 1, featuring a cylindrical configuration fabricated from stainless steel, a material selected for its resilience in extreme thermal environments. The reactor's specific dimensions, encompassing a 3.5 cm diameter, a 15 cm length, and a wall thickness of 2.5 mm, are strategically determined to facilitate optimal thermal conductivity and accommodate the requisite volume of biomass feedstock. Thermal regulation is a critical aspect, managed by an electric heating system and monitored by a digital controller, ensuring the maintenance of precise operational temperatures requisite for pyrolysis. The precision of the temperature monitoring system is exemplified by its 1°C accuracy, with data systematically recorded, providing an accurate log for comprehensive analysis. This intricate arrangement highlights the reactor's advanced engineering, designed to achieve



(a) Reactor

(b) Cross section of reactor

Fig. 1 Biomass pyrolysis reactor

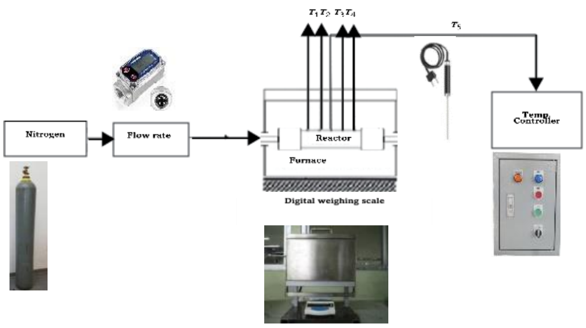


Fig.**2** Schematic of the torrefaction experiment

precision, reliability, and efficacy in the biomass pyrolysis process.

Figure 2 shows the schematic diagram of the torrefaction experiment. The biomass pyrolysis reactor was loaded into a 3-kW electric furnace. The reactor was positioned on a stand situated over a digital scale, having a 0.01 g resolution. The weight reduction of the torrefied biomass was determined by comparing its starting weight to its subsequent weight.

In the experiment, nitrogen gas was released through the reactor during the experiment to make the experimental conditions in an inert atmosphere. The volumetric flow of nitrogen gas can be adjusted with a rotameter, the accuracy of which is ±2%. The torrefaction temperature can be adjusted with a digital temperature controller (SHIMAX MAC3 Series). Five thermocouples type K (range: 0 – 800 °C, ± 0.4 °C) are mounted along the length of the reactor. The temperature distribution inside the reactor was recorded with a data logger (GRAPHTEC midi LOGGER GL220). Instrument accuracy was ±1 °C.

A 20g sample was introduced into the reactor, followed by heating the electric furnace at 20 °C/min to attain the target temperature for torrefaction analysis. Concurrently, nitrogen gas was flowed through the reactor at a rate of 1,000 ml/min. Flowing nitrogen gas through the reactor displaces oxygen and volatile compounds, creating a confined environment. For this experiment, operating temperatures ranged from 200 °C to 300°C, with residence times between 20 and 60 minutes.

2.3 Proximate analysis

Proximate analysis is a straightforward method that involves subjecting biomass to various conditions to ascertain the correlations among moisture content, volatile matter, ash content, and fixed carbon. Moisture (*M*) The biomass was dried in a hot air oven at a temperature of 105 °C for 24 hours according to ASTM D4959-00 until the biomass was dry and the weight was constant. The weight lost after baking can be calculated from Equation 1.

$$M(\%) = (\frac{A-B}{A})x100 \quad (1)$$

Where A = Initial weight (g)
B = Drying weight (g)

Volatile Matter (*VM*) is the vapor released when biomass is heated. Volatile matter is the percentage of weight of biomass lost after deducting the moisture content of the biomass. By testing for volatile substances, biomass was incubated at a temperature of 950 °C for 7 minutes according to ASTM E872 standards after taking the biomass samples out of the laboratory muffle furnace. The biomass is cooled by placing it in a desiccator and the weight loss, which can be determined by volatile compounds, can be obtained from Equation 2.

$$VM(\%) = (\frac{B-C}{C})x100 \quad (2)$$

Where C = Weight after drying at 950 °C (g)

Ash, a noncombustible, inorganic residue, is quantified following the ASTM E1755-01 standard method for ash testing. Ash content in biomass was determined using a laboratory muffle furnace, with the specific value derived from Equation 3.

$$Ash(\%) = (\frac{D}{B})x100 \quad (3)$$

where D **=** Weight after drying at 750 °C (g)

Fixed carbon (*FC*) is a carbon compound that excludes the ashes left by organic matter after the volatile material has been expelled. The carbon constant can be obtained from Equation 4.

$$FC=100\%-M(\%)+A(\%)+VM(\%) \quad (4)$$

2.4 Heating value analysis

The heating value is essential in using biomass for fuel, as it indicates the energy released during combustion—a process where biomass reacts with oxygen to produce carbon dioxide and water, releasing heat. Two types of heating values exist: Higher Heating Value (*HHV*) accounts for all energy, including water vapor's heat of condensation, while Lower Heating Value (*LHV*) excludes this condensation energy. These values are crucial for evaluating the effectiveness of biomass fuels in combustion-driven energy applications. The heating value is ascertained with a bomb calorimeter through isothermal or adiabatic processes. Prior to testing, calibration is required using a standard substance to set the calorimeter's heat capacity, ensuring precise readings

In this test, the *HHV* was determined using direct combustion in an Adiabatic bomb calorimeter. This method measures the enthalpy change between the initial substance and the products, conforming to the ASTM E711 standard.

3. Result and discussion

3.1 Particle size distribution through sieve analysis

Sieve analysis is a technique used to determine the particle size distribution of a material. The process involves sorting

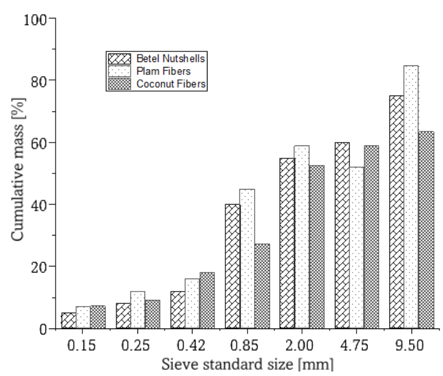


Fig.3 Distribution of particle size in sieve analysis

particles through sieves of varying mesh sizes to categorize them into different size ranges. Figure 3 illustrates the particle size distribution obtained through sieve analysis. The graph shows that a standard sieve facilitates the sorting of particles from sizes as small as 0.85 mm to as large as 37.5 mm. Particles within the 3-5 mm range are particularly relevant. These dimensions can be achieved through grinding, with an expected retrieval rate of around 55-60% for materials such as betel nut shells, palm fibers, and coconut fibers.

3.2 Properties analysis of betel nutshells before torrefaction

The assessment of biomass properties involves two essential elements: the proximate analysis and the higher heating value. Proximate analysis identifies the basic composition of biomass, including moisture, volatile matter, ash, and fixed carbon. Thermogravimetric Analysis (TGA) quantifies a material's thermal stability and composition by measuring weight changes over temperature or time in a controlled setting

Figure 4 presents values from a Thermogravimetric Analysis (TGA) conducted on pretreated betel nutshells, an agricultural by-product. The test heated the sample from 50°C to 900°C at 10°C/min. After pretreatment, including baking at 105°C for 24 hours and resizing to 3-5 mm particles, the biomass showed 76.3% volatile matter, 22.02% fixed carbon, and 1.61% ash by weight. In essence, TGA offers a temperature-weight profile, allowing deduction of moisture, volatile matter, and ash content. For accuracy, standardized procedures should be applied

Figure 5 presents a proximate analysis of betel nutshells in relation to coconut and palm fibers, conducted before torrefaction as per ASTM standards. The data revealed that volatile matter dominated the composition of betel nutshells, constituting up to 69.93%. This was succeeded by fixed carbon,

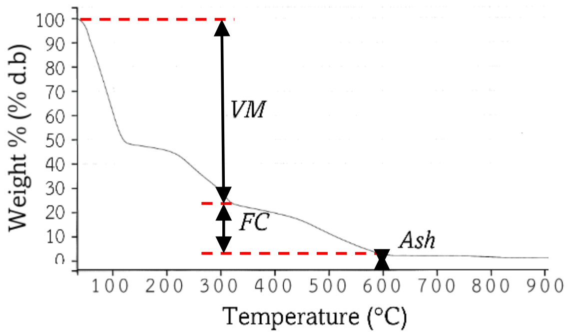


Fig.4 Proximate analysis of Betel nutshells using the TGA

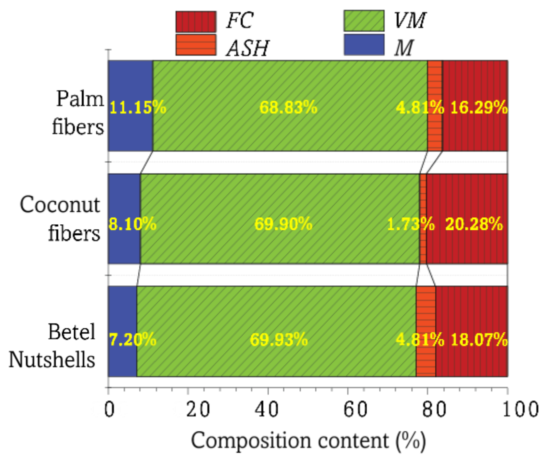


Fig. 5 Composition contents of biomass before torrefaction

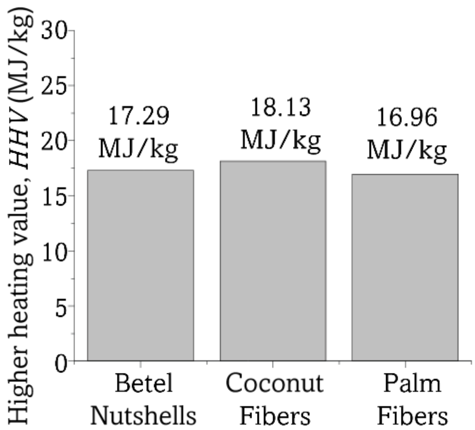


Fig.6 *HHV* of biomass before torrefaction

moisture, and ash contents, recorded at 18.07%, 7.20%, and 4.81% respectively. A comparative assessment of betel nutshells with coconut and palm fibers showed that the fixed carbon, moisture, and ash contents were relatively uniform among the three biomass samples. However, a distinct variance emerged in moisture content, with palm fiber, post-pretreatment, showing the most significant moisture level at 11.15%. Such heightened moisture levels in the biomass imply persistent infiltration by water molecules, resulting in a rise in the carbon-to-hydrogen and carbon-to-oxygen ratios.

The higher heating value (*HHV*) indicates the maximum heat produced from a biomass's complete combustion in oxygen-rich conditions. Essentially, *HHV* gauges a biomass's total energy potential, determined by its elemental makeup, primarily carbon, hydrogen, and oxygen. *HHV* becomes essential when assessing biomass for energy or heating applications.

Figure 6 presents the *HHV* of betel nutshells in comparison with coconut and palm fibers after undergoing pretreatment, which includes reducing humidity to the standard of 105 °C for 24 hours and adjusting the size to a range of 3-5 mm. The *HHV* derived from bomb calorimeter measurements for each type of biomass was repeated 10 times and then averaged. The findings indicate that after initial conditioning, betel nutshells have an *HHV* of approximately 17.29 MJ/kg. Compared to coconut and palm fibers, betel nutshells show similar characteristics, suggesting their potential as an alternative to traditional solid biomass fuels, given their comparable Higher Heating Values (HHVs). However, the data indicate that palm fiber has the lowest HHV, around 16.96 MJ/kg, potentially due to its higher moisture content and lower fixed carbon content.

3.3 The influence of operating temperature on the torrefaction

In this section, betel nutshells weighing 20 g were torrefied at operating temperatures of 200, 250, and 300 °C for a residence time of 40 minutes. Subsequently, their internal component composition was analyzed. The study was repeated 10 times to establish an average value. The torrefaction process, a thermal chemical transformation similar to slow pyrolysis, occurs at temperatures between 200-300 °C. In this temperature range, only part of the hemicellulose decomposes. The process yields products in three states: solid (biochar), liquid (tar), and vapor. This vapor can be harnessed to generate combustible gas or condensed to produce a liquid known as bio-oil.

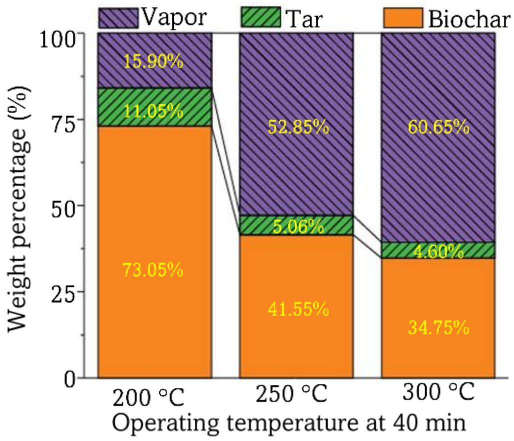


Fig.7 Products from betel nutshells after torrefaction (At residence time 40 min)

Figure 7 showcases the average products derived from the torrefaction process at different operating temperatures, all with a consistent residence time of 40 minutes. The data from the study suggests that varying the temperature leads to differences in the quantity of products produced. At 200 °C for 40 minutes, the predominant product was char, making up 73.05%, followed by vapor at 15.90% and tar at 11.05%. Raising the temperature to 250 °C for the same duration brought about rapid changes in the product composition: the char and tar quantities saw notable reductions, while the vapor content rose sharply to 52.85%. The proportions were 41.55% for char and 5.60% for tar oil. Further testing at 300°C for 40 minutes showed results mirroring those at 250°C; although char and tar amounts decreased and vapor increased, the shifts in quantities were relatively modest compared to the 250 °C results**.**

The correlation between temperature rise and product conversion suggests that increasing temperatures modify the biomass's molecular structures, particularly impacting hemicellulose. Between 200-250 °C, there's a substantial vapor release due to hemicellulose's rapid degradation, contrasting with the decreased char and tar as biomass turns to vapor. From 250-300 °C, similar patterns occur but are less marked, attributed to the swift hemicellulose breakdown around 240 °C. Beyond this, while further cellulose degradation releases more vapor, the reaction slows. After studying the products obtained from the torrefaction process of betel nutshells at various operating temperature ranges, the next step of the study is to test the char obtained and analyze the effects of operating temperature on the composition content of the betel nutshells using an approximate analysis method.

Figure 8 illustrations the test results indicating that the compositional quantities change when the temperature varies. The betel nutshells, after initial conditioning, has the highest component quantity being the volatile matter, which is as high as 69.93%. This is followed by fixed carbon, moisture content, and ash, with amounts of 18.07%, 7.20%, and 4.81% respectively. Upon subjecting the betel nut husk to the torrefaction process, alterations in the compositional ratios were observed to be directly correlated with temperature variations. With an increase in temperature, there is a corresponding rise in the content of fixed carbon and ash. Conversely, the content of volatile matter and moisture demonstrates a decline. The underlying mechanism suggests that heightened thermal conditions lead to the disintegration of internal bonds, thereby expelling moisture and volatile compounds. Consequently, the residue is predominantly comprised of carbonaceous elements, specifically fixed carbon, and the incombustible component, which is characterized as ash.

The study of the influence of operating temperature on the *HHV* during the torrefaction reaction is illustrated in Figure 9. The horizontal axis represents operating temperature, while the vertical axis indicates the *HHV*. The test results show that the *HHV* at operating temperatures of 200, 250, and 300°C for a duration of 40 minutes are 23.50, 24.11, and 24.24 MJ/kg, respectively. From this data, it can be deduced that as the temperature used in the torrefaction process increases, there's a tendency for the heating value to rise. The increase in the heating value is significantly different in the temperature range of 200-250°C, while only a slight difference is observed in the range of 250-300 °C.

The observed phenomenon can be attributed to the inherent nature of torrefaction as a thermochemical treatment. This process instigates the breakdown of chemical bonds within the biomass structure; consequently, these reactions facilitate the release of volatile compounds characterized by a lower molecular weight. As the torrefaction temperature intensifies, there is a marked enhancement in the carbon-to-hydrogen and carbon-to-oxygen ratios.

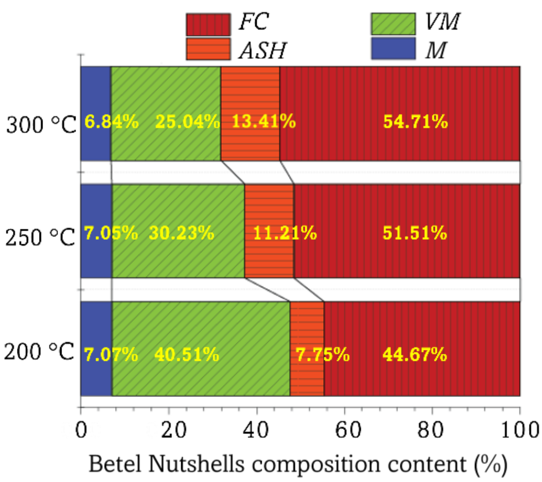


Fig.8 Composition content of torrefied betel nutshells (At residence time 40 min)

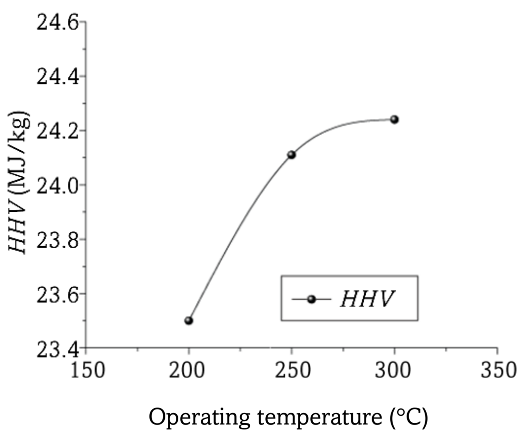


Fig. 9 *HHV* trend of torrefied betel nutshells (At residence time 40 min)

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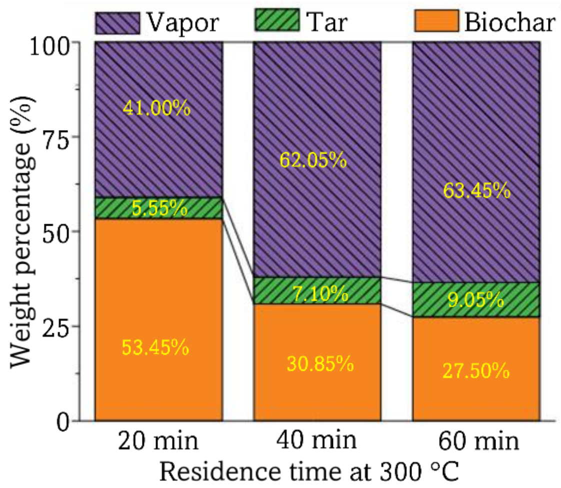

Fig.10 Products from torrefied betel nutshells (At operating temperature 300 °C)

3.4 The influence of residence time on the torrefaction

In this study, the effect of residence time on torrefaction was investigated at the operating temperature of 300 °C, chosen for its maximum heating value in section 3.3. The selected residence times were 20, 40, and 60 minutes.

The research focused on how residence time adjustments impacted the torrefaction yield composition, with results displayed in Figure 10. Initially, the products resulting from the torrefaction at various residence times were examined. The findings showed that at an operating temperature of 300°C and a residence time of 20 minutes, the major product output was char at 53.45%, followed by vapor at 41.00%, and tar at 5.55%. When the residence time was increased from 20 minutes to 40 minutes, there was a rapid change in the product yield: the amounts of char and tar decreased significantly, while the vapor volume increased substantially, with its proportion being highest at 62.05%, followed by char at 30.85%, and tar at 7.10%. Subsequent testing at 60 minutes revealed that the product formation trend was consistent with that observed at 40 minutes, where char and tar quantities decreased, and vapor increased. However, these changes were not drastically different in quantity.

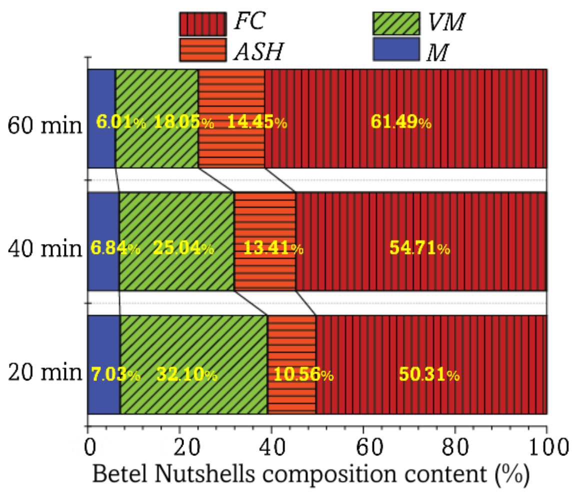

Fig.11 Composition content of torrefied betel nutshells (At operating temperature 300 °C)

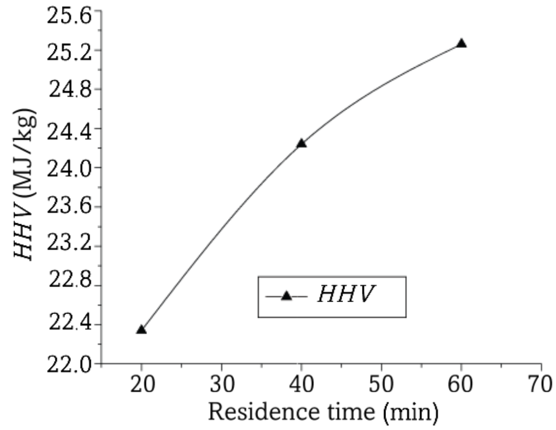

Fig. 12 *HHV* trend of torrefied betel nutshells (at operating temperature 300 °C)

Increasing the residence time influences the changes in the composition content of betel nutshells, as shown in Figure 11. The study found that the extended time affects the degradation of the molecular bonds of the compounds in the biomass. Between the residence time range of 20-40 minutes at an operating temperature of 300°C, the cellular wall components that break down are primarily hemicellulose. The research also identified that during this period, there is a high rate of hemicellulose degradation, resulting in an increased release of volatile compounds in the system. This coincides with a rapid decrease in the quantities of char and tar as the biomass transitions into volatile gases. In the time span between 40-60 minutes, product changes follow the same trend as observed in the 20-40 minute range, but the changes are only slight. The testing indicates that the degradation of hemicellulose occurs predominantly within the first 40 minutes. The heating values of betel nutshells, subjected to the torrefaction process at temperatures of 200, 250, and 300°C for 40 minutes, were analyzed. The test results are shown in Figure 12. The horizontal axis displays the operating temperature and the vertical axis shows the higher heat values. The test results reveal that the heat values of the betel nut shells at temperatures of 200, 250, and 300°C for 40 minutes are 23.50, 24.11, and 24.24 MJ/kg, respectively. From the mentioned data, it can be observed that as the temperature used in the torrefaction process increases, the heat value tends to rise. The rate of increase in heat value varies significantly in the temperature range of 200-250°C. However, the increase in heat value between the temperature ranges of 250-300°C is only slightly different.

The reason for this is because torrefaction is a heat treatment process. This heat destroys the chemical bonds of the biomass structure through dehydration and decarboxylation reactions (Zhang *et al.*, 2022). As a result, there is a loss of low molecular weight volatile compounds. This causes the ratio of carbon to hydrogen and the ratio of carbon to oxygen to significantly increase as the temperature used in the torrefaction process rises.

3.5 The properties of betel nutshells components comparing with those of palm plants after the torrefaction

Previous sections indicate that torrefied betel nutshells at 300°C for 60 minutes yields the maximum higher heating value. This section makes a comparative analysis with other

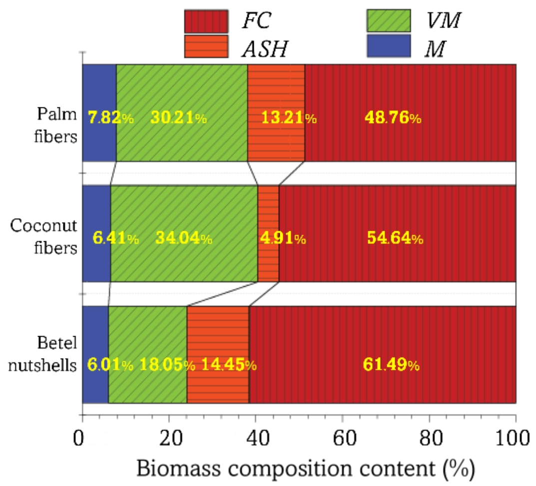

Fig. 13 Composition content of biomass (Operating temperature 300 °C and residence time 40 min)

agricultural residues, namely coconut and palm fibers, under these optimal torrefaction conditions.

Figure 13, from the comparison of all three types of biomass, indicates a similar compositional trend: the highest quantity is fixed carbon, followed by volatile matter, ash, and moisture, in that order. Tests using an approximate analysis showed that betel nutshells contain up to 61.49% fixed carbon. A high proportion of fixed carbon and low moisture content indicate a high ratio of carbon to oxygen and carbon to hydrogen, which in turn results in a higher heating value of the biomass.

The analysis of the higher heating values for three biomass types using a bomb calorimeter, depicted in Figure 14, revealed that coconut fiber possesses the highest value, reaching 25.83 MJ/kg. This data is significant for torrefied solid fuel, which commonly varies between 20-25 MJ/kg. Betel nutshells also exhibit a considerably high value, nearly matching coconut fiber, at 25.20 MJ/kg. Meanwhile, palm fiber has an *HHV* of approximately 23.48 MJ/kg

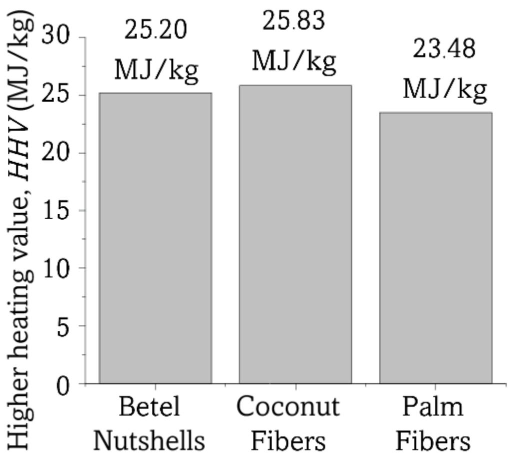

Fig. 14 *HHV* of biomass after torrefaction (Operating temperature 300 °C and residence time 40 min)

As for the reason why palm fiber has the lowest higher heating value, it's because it has a lower proportion of fixed carbon and a higher moisture content compared to betel nutshells and coconut fiber, resulting in a lower higher heating value. Even though betel nutshells have the highest fixed carbon content after being roasted at 300°C for 60 minutes, they still have a slightly lower *HHV* than coconut fiber. From past literature studies, it's found that in addition to the high proportion of fixed carbon and low moisture content leading to highest higher heating value in biomass fuels, the proportion of volatile matter also plays a role in increasing the *HHV*. Coconut fiber has more volatiles than betel nut shells by approximately 15.99% in the tests

3.6 Energy yield

In this section, the discussion focused on the energy yield. Energy yield is the yield of energy as a product of energy per unit weight, where the yield of energy reflects the effect of stored energy. When the biomass goes through the torrefaction process, it can be calculated as Equation (5)

$$y_{energy}(\%) = \left(\frac{m_{char}}{m_{biomass}}\right) x \left(\frac{HHV_{char}}{HHV_{biomass}}\right) x100 \quad (5)$$

Where m_{char} is biomass weight after being torrefied [kg], $m_{biomass}$ is biomass weight before being torrefied [kg], HHV_{char} is high heating value after being torrefied [MJ/kg], and $HHV_{biomass}$ is high heating value before being torrefied [MJ/kg].

Table 1 presents the study results regarding the energy yield of betel nutshells when the residence time is held constant, but the operating temperature varies. Initial observations indicate that the untreated betel nutshells have an energy value of 17.29 MJ/kg. However, after undergoing torrefaction at an operating temperature of 200 °C, the higher heating value increases to 23.50 MJ/kg. This suggests an enhancement of 6.01 MJ/kg in the higher heating value due to torrefaction, resulting in a charcoal product yield of 14.61 g and an energy yield of 99.29%. Yet, when the operating temperature was increased to 250 °C, there was a slight rise in *HHV* by 0.61 MJ/kg, while the product yield reduced to 8.31 g, and the energy yield was 57.94%. Further increasing the operating temperature to 300 °C led to a marginal higher heating value increment of 0.13 MJ/kg, a decrease in the product yield to 6.95 g, and an energy yield of 48.72%. It is apparent that as the temperature escalates, the energy yield decreases. For biomass undergoing the torrefaction process, comparisons with previous research revealed that the tested biomass's higher heating values are within a reference range of 20-24 MJ/kg. Thus, the optimal conditions for the torrefaction process seem to be an operating temperature of 200 °C with a residence time of 20 minutes, as it provides a high energy yield, an acceptable higher heating value, and a superior charcoal product yield. Any increase in temperature only marginally increases the higher heating value while significantly reducing the charcoal yield.

Table 1
Effect of operating temperature on the *HHV*

Temp (°C)	Time (min)	$m_{biomass}$ (g)	m_{char} (g)	HHV_{char} (MJ/kg)	y_{energy} (%)
	Raw betel nutshells			17.29	
200	40	20.00	14.61	23.50	99.29
250	40	20.00	8.31	24.11	57.94
300	40	20.00	6.95	24.24	48.72

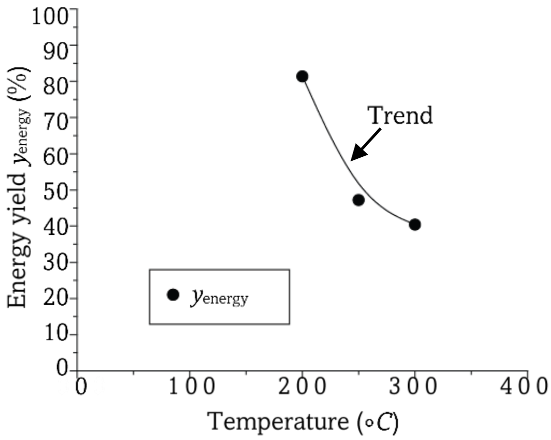

Fig.15 Energy yield trend of betel nutshells (at 40 min)

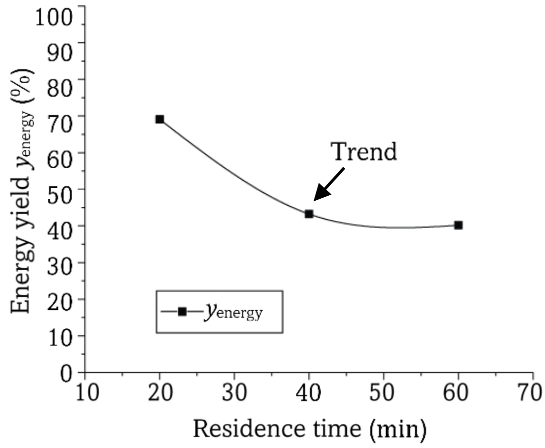

Fig.16 Energy yield trend of betel nutshells (at 300 °C)

From Figure 15, it is observed that the energy yield is significantly higher when initiating the torrefaction reaction. However, as the operating temperature increases or the duration extends, the energy yield notably decreases. The trend of the energy yield for the betel nutshells appears to follow a parabolic curve.

From Table 2, the study investigates the energy yield of betel nutshells when the operating temperature remains constant, but the residence time changes. It can be observed that after the initial conditioning, the betel nutshells have a higher heating value of 17.29 MJ/kg. After torrefaction at an operating temperature of 300 °C and a residence time of 20 minutes, the HHV increases to 22.34 MJ/kg. This suggests that the torrefaction reaction results in an increase of up to 5.05 MJ/kg in higher heating value. Additionally, the product yield is 10.69 g, with an energy yield of 69.06%. However, when the residence time is extended to 40 minutes, the higher heating value increases by 1.9 MJ/kg, but the product quantity decreases to 6.17 g, resulting in an energy yield of 43.25%. Further increasing the residence time to 60 minutes sees the higher heating value rise by another 1.02 MJ/kg, while the product quantity diminishes to 5.50 g, yielding an energy output of 40.18%. It is evident that as the residence time extends, the energy yield decreases. When comparing the properties of the biomass that underwent the torrefaction process with past research, it is found that the tested biomass higher heating value falls within the reference range of 20-24 MJ/kg. This is due to the high energy yield and the higher heating value being within the acceptable standard, along with the produced charcoal being of a high quality. Increasing the temperature slightly elevates the higher heating value, but reduces the quantity of charcoal produced. Figure 16 aligns with the results from Figure 15, showing that energy yield is initially high during the onset of torrefaction but decreases significantly with higher temperatures or longer residence times. The energy yield trend for betel nutshells forms a parabolic graph, consistent with findings from similar torrefaction research.

Table 2
Effect of residence time on the HHV

Temp (°C)	Time (min)	$m_{biomass}$ (g)	m_{char} (g)	HHV_{char} (MJ/kg)	y_{energy} (%)
Raw betel nutshells				17.29	
300	20	20.00	10.69	22.34	69.06
300	40	20.00	6.17	24.24	43.25
300	60	20.00	5.50	25.26	40.18

4. Conclusion

In summary, this study highlights the potential of betel nutshells as a substantial alternative in the domain of solid biofuel, primarily due to their significant a carbon-rich profile that contributes to their elevated heating values, comparable to established biofuels such as coconut and palm fibers. Critical insights indicate that the torrefaction process intensely influences the fuel characteristics of betel nutshells, with the operating temperature and residence time of torrefaction emerging as crucial parameters. The observation that a 60-minute exposure to a 300°C environment maximizes the higher heating value is significant, with this optimization attributed to the rapid breakdown of hemicellulose and the resulting increase in both carbon-to-hydrogen and carbon-to-oxygen ratios.

Nonetheless, Increasing the operating temperature further negatively influences the energy yields, highlighting the importance of careful parameter changes during torrefaction to thoroughly capitalize on the biofuel potential of betel nutshells. The study also reveals that despite a decrease in mass post-torrefaction, there is a substantial augmentation in higher heating value, from 17.29 MJ/kg to 23.50 MJ/kg, denoting an improvement in energy efficiency and fuel capacity. This evidence-based affirmation fortifies the position of betel nutshells as a noteworthy contender in the sphere of sustainable energy alternatives.

5. Recommendations

It is recommended that future studies on torrefied betel nutshells, palm, and coconut fibers incorporate SEM and XRD analyses, as these advanced methodologies are pivotal in revealing intricate details about structure and composition. These techniques provide the means to examine microstructural evolutions and shifts in crystallinity post-torrefaction, playing a crucial role in refining bioenergy conversion processes. This recommendation is part of strategic planning that underscores the importance of SEM and XRD analyses in advancing the effectiveness and dependability of biomass as a renewable energy resource.

Conflicts of Interest: There are no conflicts of interest in this research.

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