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Effect of Torrefaction Process on the Physicochemical Properties of Solid Fuel from Palm Kernel Shells

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ABSTRACT

This research investigates the effects of torrefaction on the characteristics of solid fuel made from palm kernel seed (PKS). The torrefaction process was conducted on raw PKS to improve its energy density and combustion efficiency. Torrefaction was carried out at 400°C at different durations (30, 40, and 50 minutes), with the goal of improving the energy density and combustion efficiency of raw PKS. The torrefied PKS was then ground and sieved into particle sizes of 150μm and 300μm. After being blended with high-density polyethylene (HDPE), the torrefied PKS was compacted using hot press machine into solid fuel and tested for its physicochemical properties. The results indicated that PKS torrefied for 50 minutes with particle size of 300 μm exhibited optimal characteristics, with a high heating value (HHV) of 23.22 MJ/kg. The particle size plays a role, with finer particles (150μm) having lower HHV values compared to coarser particles (300μm). Additionally, the inclusion of HDPE affected the properties of the solid fuel. Morphological analysis using scanning electron microscopy provided insights into its structural features.

Keywords: palm kernel shell, solid fuel, torrefaction, physicochemical properties

1. INTRODUCTION

Malaysia is well-known for its palm oil industry, which produces a significant amount of palm kernel shell (PKS) as a byproduct (MPOB, 2022). As the world increasingly prioritizes sustainable energy sources, PKS is gaining attention as a renewable solid fuel due to its abundance and potential for energy production. The utilization of PKS as a solid fuel continued to align with Malaysia's commitment to reducing greenhouse gas emissions and promoting sustainable development (12th Malaysia Plan, 2021). PKS combustion in biomass power plants contributed to displacing fossil fuels and reducing carbon footprints.

However, dealing with the challenges of moisture content, handling characteristics, and combustion efficiency requires innovative approaches to improve the usefulness of palm kernel shells (PKS) as a solid fuel. Torrefaction is a transformative thermal treatment process that alters the physical and chemical properties of PKS, thereby enhancing its energy density, grindability, and combustion behavior.

The primary aim of this study is to examine the effect of torrefaction treatment with varying residence times and particle sizes on the physicochemical properties of the resulting solid fuel. The quality of solid fuel refers to its suitable size for transportation, high density, and energy content (Aizuddin *et al*., 2014). Furthermore, a high-quality solid fuel should have low moisture and ash content to ensure a consistent and complete combustion process (Oladeji, 2012).

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2. MATERIAL AND METHODS

2.1 Materials

The first step in producing solid fuel is to gather raw palm kernel shells (PKS) from Taclico Company Sdn. Bhd, located in Kulim, Kedah. It is essential to use a binder to consolidate the raw material. In this research, a high-density polyethylene (HDPE) plastic was selected and obtained from a local supplier. At the same time, HDPE also is an ecologically friendly solution to improve charcoal pellets or solid fuel properties (Garrido *et al*., 2017).

2.2 Apparatus and experimental procedure

The first stage of this research starts with the torrefaction of the raw PKS. The raw PKS were subjected to torrefaction in a furnace at a controlled temperature of 400°C, with varying heating times of 30, 40, and 50 minutes. Following this, the torrefied PKS were ground into finer particles and sieved into sizes of 150 μm and 300 μm. Next, the solid fuel is produced by compacting the torrefied PKS blended with HDPE in a 60:40 ratio using a hot press machine at 180°C for 15 minutes.

2.3 Analysis

The physicochemical properties of the PKS solid fuel resulting from the torrefaction process were assessed through physical, proximate, and combustion analysis. Physical analysis was used to measure the solid fuel's density, while proximate analysis was carried out to determine its ash content, volatile matter, and fixed carbon. The amount of energy density is analyzed through combustion analysis. Each analysis was repeated three times to ensure the precision of the obtained results.

2.3.1 Physical Analysis

The effect of the torrefaction process on the physical of the solid fuel produced was determined based on the density of the solid fuel produced. Density was determined from the ratio of the mass over the volume of the torrefied solid fuel. The mass and volume of each sample were taken by weighing the torrefied solid fuel on a digital scale and using the formula of a cylinder, respectively. Equation 1 shows the formula for calculating the density.

$$Density, \rho = \frac{mass\ (g)}{volume\ (cm^3)} \tag{1}$$

2.3.2 Proximate Analysis

In this analysis, the compositions of ash, volatile matter, fixed carbon, and moisture are analyzed. The moisture content (MC) was obtained by using oven drying technique and calculated by using Equation 2 where, W_w is the wet weight of the sample and W_d is the weight of the dried sample.

$$MC(\%) = \frac{(W_w - W_d)}{(W_d)} x\ 100 \tag{2}$$

The ash content (AC) was determined according to ASTM E1755-01 (2007), which required the solid fuel to be burned at 400°C for 4 hours in the furnace, and the balance is weighed by using an analytical balance. The percentages of content calculated using Equation 3.

$$AC\ (\%) = \frac{Weight\ of\ ash}{Weight\ of\ sample} x\ 100 \quad (3)$$

The volatile matter (VM) in a solid fuel sample was determined by placing it in a crucible, covering it with a lid, and heated in a furnace. The weight loss was recorded as a percentage of the volatile matter. The percentage of volatile matter was calculated using Equation 4 where W_i is the initial weight of the sample and W_f is the final weight of the sample.

$$VM\ (\%) = \frac{(W_i - W_f)}{(W_i)} x\ 100 \quad (4)$$

Finally, the fixed carbon (FC) is the solid combustion product that remains after a coal particle is heated and the volatile component is driven off, and its calculation is presented in Equation 5.

$$\text{FC}\ (\%) = 100\ \% - (MC + AC + VM) \quad (5)$$

2.3.3 Combustion Analysis

The high heating value (HHV) of solid fuels can be determined and analyzed using an Oxygen Bomb Calorimeter. This measurement is performed to determine the heat or energy released by the fuel during complete combustion. The measured values are typically displayed in units of MJ/kg.

2.3.4 Morphological Analysis

The morphology of the solid fuel is tested using a Scanning Electron Microscope (SEM). The analysis aims to compare the surface morphology of the solid fuel made from different torrefaction treatment and particle size.

3. RESULTS AND DISCUSSION

3.1 Physicochemical properties

The effects of torrefaction treatment and particle size on the properties of the torrefied PKS solid fuel were assessed through physicochemical properties analysis which are including physical, proximate, ultimate and high heating value analysis.

3.1.1 Physical analysis

The outcome of the torrefaction process on the raw PKS and the solid fuel produced is illustrated in Figure 1 and 2, respectively.

Figure 1. PKS after torrefaction.

Figure 2. Solid fuel made from torrefied PKS mixed with HDPE.

Table 1 shows that the density of the torrefied PKS solid fuel produced from different torrefaction times was found to be in the range of 851.25 to 1187.95g/cm³. The lowest density was found in torrefied PKS solid fuel produced from 30 minutes of torrefaction treatment, while the maximum density was found in torrefied PKS solid fuel produced from 50 minutes of torrefaction treatment.

Table 1. Effect of torrefaction time and particle size on the density of the solid fuel.

Torrefaction Time (min)	Density (g/cm³)	
	150μm	**300μm**
30	851.25	1105.45
40	865.55	1158.25
50	898.75	1187.95

From the results in Table 1, it can be concluded that torrefaction time influences the solid fuel's physical strength. Torrefaction is a thermal treatment process that modifies biomass such as PKS, enhancing its grindability and reducing fiber size. As the torrefaction time increases, there is a greater degree of depolymerization and devolatilization within the PKS material. This thermal degradation softens the lignin present in PKS, facilitating better compaction and resulting in higher-density solid fuel products. According to Tumuluru *et al.* (2011), softened lignin plays a crucial role in enhancing the compactability of torrefied materials, thereby contributing to the observed increase in density with longer torrefaction times.

Moreover, the particle size of torrefied PKS also influences its density. Generally, finer particles tend to pack more densely compared to larger particles due to increased surface area and inter-particle contact. This is evident in Table 1, where PKS particles of 300 μm size consistently exhibited higher densities across all torrefaction times compared to particles of 150 μm size.

3.1.2 Proximate analysis

Table 2 presents the effects of torrefaction treatment and particle size on the proximate properties of torrefied PKS solid fuel, focusing on moisture content, fixed carbon, volatile matter, and ash content. These properties are crucial indicators of the quality and combustion characteristics of solid fuels derived from torrefied PKS.

Table 2. Effect of torrefaction treatment and particle size on the MC, VM, FC and AC of the torrefied PKS solid fuel.

Component (%)	Particle Size/Torrefaction Treatment					
	150μm			**300μm**		
	T1 (30 s)	**T2 (40 s)**	**T3 (50 s)**	**T1 (30 s)**	**T2 (40 s)**	**T3 (50 s)**
Moisture Content (MC)	9.09	8.33	7.14	8.57	7.56	6.25
Fixed Carbon (FC)	42.43	44.87	47.43	46.80	48.65	51.49
Volatile Matter (VM)	40.73	39.94	39.68	38.56	38.36	37.9
Ash Content (AC)	7.75	6.86	5.75	6.07	5.43	4.36

The results show that torrefaction treatment significantly enhances the fixed carbon content of PKS solid fuel, with values ranging from 42.43% to 51.49%. High fixed carbon content is vital for efficient combustion processes, as it contributes significantly to the thermal energy release during burning

(Du *et al*., 2014). Despite the lower volatile matter content observed in torrefied PKS, which can make ignition challenging, the increased fixed carbon content suggests improved combustion efficiency and reduced smoke emissions.

Torrefaction treatments, especially with longer durations (from 30 s to 50 s), effectively reduce the moisture content of torrefied PKS solid fuel. The moisture content decreased from 9.09% to 7.14% for 150 μm particles and from 8.57% to 6.25% for 300 μm particles. Low moisture content is critical as it enhances the higher heating value (HHV) of solid fuel, ensuring more efficient energy generation (Wang *et al*., 2009). This reduction underscores the effectiveness of torrefaction in enhancing the fuel's energy density and reducing transportation and storage costs.

Torrefaction treatments also lead to a reduction in ash content in the torrefied PKS solid fuel, ranging from 4.36% to 7.75%. Lower ash content is desirable as it minimizes residue after combustion, thereby improving combustion efficiency and reducing maintenance requirements in combustion systems. The decrease in ash content further highlights the effectiveness of torrefaction in modifying the chemical composition of PKS, making it more suitable for clean and efficient energy production.

The findings from Table 2 collectively indicate that torrefaction treatment improves the overall quality of torrefied PKS solid fuel by enhancing fixed carbon content, reducing moisture content, and lowering ash content (Nigran *et.al*, 2019). These improvements not only enhance the combustion efficiency and energy yield but also contribute to environmental sustainability by reducing emissions and residue formation (Wilk & Magdziarz, 2017).

3.1.3 Combustion analysis

In this analysis, the parameter being measured is the high heating value (HHV). HHV represents the maximum amount of energy that can be obtained from the combustion of a solid fuel. It considers the chemical composition of the solid fuel and the heat released as the solid fuel reacts with oxygen to form combustion products, such as carbon dioxide, water vapor, and other byproducts. Table 3 shows the effect of torrefaction treatment and particle size on the HHV of the torrefied PKS solid fuel.

Table 3. Effect of torrefaction treatment and particle size on the HHV of the torrefied PKS solid fuel.

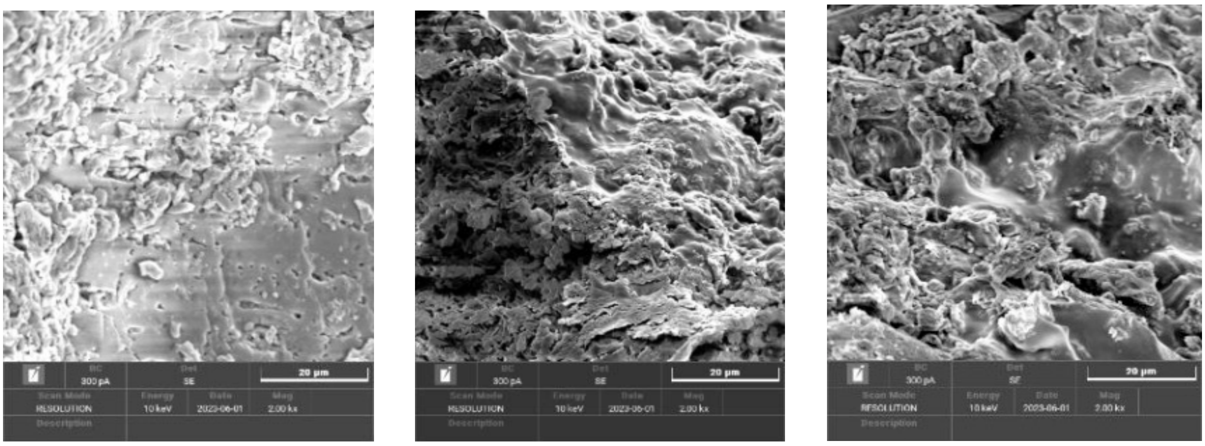
Torrefaction Treatment (sec)	**HHV (MJ/kg)**	
	Particle Size	
	150μm	**300μm**
30	21.69	22.48
40	21.84	22.81
50	22.04	23.22

From Table 3, the results demonstrate that treating PKS solid fuel with torrefaction significantly increases its HHV. When the torrefaction duration was increased from 30 to 50 minutes, the HHV also increased from 21.69 to 22.04 MJ/kg for 150μm particle size, and from 22.48 to 23.22 MJ/kg for 300μm particle size. This improvement in HHV means that the energy density and combustion efficiency of the fuel increased, which might be due to the changes in its structure and reduced oxygen content during torrefaction. It was also noted that the particle size plays a role, with finer particles (150μm) having lower HHV values compared to coarser particles (300μm). These findings emphasize the importance of torrefaction parameters and particle size in optimizing the energy properties of PKS solid fuel for sustainable energy applications.

The highest value of 23.22 MJ/kg was obtained by solid fuel made from torrefied PKS at 50 minutes with particle size of 300μm. When compared to other published HHV of solid fuel done by other researchers such as rice husk solid fuel (13.4 MJ/kg) (Oladeji, 2010), and rice husk and banana residue solid fuel (16.4 MJ/kg) (Nazari *et al.*, 2019), it showed that the torrefaction of biomass enhance the HHV. The results in Table 3 also indicate that all solid fuel produced fulfils the minimum energy released required for making commercial solid fuel as stated in DIN 51731, which is more than 17.5 MJ/kg.

3.2 Morphological analysis

The scanning electron microscopy (SEM) analysis provided valuable insights into the morphological changes of torrefied palm kernel seed (PKS) solid fuel, mainly focusing on particles sized at 300μm. This particle size was chosen due to its optimal combustion properties, exhibiting high heating values (HHV) ranging from 22.48 to 23.22 MJ/kg, as shown in Table 3. Figure 3 illustrates SEM images of the torrefied PKS solid fuel at different torrefaction durations (30 s, 40 s, and 50 s). Each image (a), (b), and (c) represents a distinct surface morphology resulting from varying degrees of torrefaction. These morphological differences are crucial indicators of the structural changes occurring within the solid fuel during the torrefaction process.



(a) (b) (c)

Figure 3. SEM images of torrified PKS solid fuel with particle size of 300μm under different torrefaction duration. (a) 30 s (b) 40 s (c) 50 s.

In Figure 3(a), the SEM image reveals a relatively smooth surface with minimal structural changes after 30 sec torrefactions. As the torrefaction duration increased to 40 sec (Figure 3(b)), there was noticeable surface roughening and structural modification, indicating ongoing thermal degradation and chemical transformation within the PKS particles. By 50 sec of torrefaction (Figure 3(c)), the surface morphology shows pronounced roughness and structural alterations, suggesting further enhancement of the solid fuel's porosity and surface area, which are favourable for improved combustion characteristics.

These SEM observations corroborate the findings from the HHV (Table 3), where longer torrefaction durations generally resulted in higher HHV values. The increased surface roughness and porosity observed in the SEM images are indicative of enhanced reactivity and combustion efficiency due to increased accessibility of reactive sites and reduced mass transfer limitations during combustion.

4. CONCLUSION

In this study, the effects of torrefaction treatment and particle size on the physicochemical properties of torrefied PKS solid fuel were thoroughly investigated. The analysis encompassed physical, proximate, and HHV assessments, providing insights into the potential of torrefaction for enhancing the suitability of PKS as a sustainable energy source. The physical analysis revealed that torrefaction treatment significantly influences the density of PKS solid fuel. Longer torrefaction durations generally resulted in higher densities, indicative of improved material compaction and structural integrity suitable for solid fuel applications. Torrefied PKS exhibited reduced moisture and ash content, crucial for enhancing combustion efficiency and minimizing environmental impact. The increase in fixed carbon content from 42.43% to 51.49% underscores the improved energy yield and combustion performance of torrefied PKS solid fuel. HHV demonstrated that torrefaction treatment significantly enhances the energy density of PKS solid fuel. The highest HHV of 23.22 MJ/kg was achieved with particles torrefied for 50 minutes at a size of 300 μm, highlighting the effectiveness of prolonged torrefaction in enhancing energy output. These findings not only surpass minimum commercial fuel standards but also compare favorably with other biomass solid fuels, emphasizing the viability of torrefied PKS for sustainable energy applications. In conclusion, the comprehensive analyses conducted in this study illustrate the transformative impact of torrefaction on the physicochemical properties of PKS solid fuel. By enhancing density, reducing moisture and ash content, and increasing HHV, torrefaction proves to be a promising pathway for upgrading biomass into a high-performance energy resource, aligning with sustainable energy goals and fostering a greener energy future.

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