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Enhancing the Grindability and Porosity of Palm Kernell Shell Through Microwave Preheating and Torrefaction for Sustainable Energy Production

Lukas Kano Mangalla*[1], Raden Rinova Sisworo[2], Luther Pagiling[3], Mansur[4]

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Abstract: Biochar from Palm Kernel Shell (PKS) can be obtained through the torrefaction process of biomass under oxygen-free conditions, offering significant potential as a material for cofiring in combustion applications. While extensive research has examined various biochar characteristics, such as its chemical composition and thermal properties, understanding its grindability and porosity remains limited. This study investigates experimentally the impact of microwave preheating and torrefaction on the grindability and porosity of palm kernel shells. PKS samples were preheated using microwave radiation at power levels of 360, 540, and 750 Watts for 10 minutes. Subsequently, each sample underwent torrefaction at temperatures of 200°C, 250°C, and 300°C for 30 minutes. Comprehensive chemical and physical analyses, including Scanning Electron Microscopy (SEM), Differential Thermogravimetric Analysis (DTG), and Differential Thermal Analysis (DTA), were employed to evaluate the modified properties of the torrefied PKS. The results highlight that the combined treatment significantly improves both grindability and porosity of PKS. Particularly, increasing microwave power levels during preheating enhances these properties, making the resultant solid products more suitable for efficient energy production processes. This study provides valuable insights into optimizing the utilization of PKS through innovative thermal treatments, contributing to sustainable biomass utilization strategies.

Keywords: *Palm kernel shell, Microwave Preheating, Torrefaction, Grindability, and Porosity.*

1. Introduction

The increasing demand for sustainable energy solutions has driven significant interest in renewable resources, with biomass emerging as a particularly promising option[1]–[4]. Biomass, which is derived from organic materials such as agricultural residues, forestry leftovers, and dedicated energy crops, serves as a renewable and carbon-neutral alternative to fossil fuels. It plays an important role in the global effort to reduce greenhouse gas emissions and mitigate climate change, thereby contributing to a more sustainable energy future. However, the efficient utilization of biomass for energy production requires improvements in its physical properties to meet the demands of modern energy applications [5]–[7]. Enhancing these properties can improve the energy density, combustion efficiency, and overall performance of biomass as a fuel. This requires advancements in processing technologies and material treatments to make biomass suitable for practical use in various energy systems. By addressing these challenges, biomass can become a more viable and effective component of the global energy mix in the future.

[1] *Mechanical Eng., Halu Oleo University, Kendari – 93232 INDONESIA ORCID ID : 0009-0002-0527-4273*
[2] *Mechanical Eng., Halu Oleo University, Kendari – 93232 INDONESIA ORCID ID : 0000-0002-0283-0302*
[3] *Electrical Eng., Halu Oleo University, Kendari – 93232, INDONESIA ORCID ID : 0009-0000-3856-6403*
[4] *Electrical Eng., Halu Oleo University, Kendari – 93232, INDONESIA ORCID ID : 0009-0006-1557-0788*
* *Corresponding Author Email: lukas.kano@uho.ac.id*

Indonesia has significant potential for biomass energy, primarily due to its extensive agricultural activities, especially in palm oil and coconut production[8]–[10]. Palm kernel shells (PKS) is abundantly available and can be utilized for energy production and many other industrial applications[10], [11]. PKS are a byproduct of the palm oil industry. Indonesia, one of the largest producers of palm oil in the world, generates vast quantities of PKS[12]. These shells have a high calorific value, typically ranging from 17.0 to 19.5 MJ/kg, making them an excellent source of renewable energy[13], [14]. Due to its high energy density and relatively low moisture content, this material is suitable for direct combustion in boilers, power plants, and as a raw material for producing biochar and activated carbon. The effective use of the biomass materials not only enhances energy production efficiency but also contributes to waste reduction and resource optimization in agricultural sectors.

Raw biomass, in its unprocessed form, often presents challenges due to its high moisture content, low energy density, and inconsistent physical properties[15], [16]. These characteristics can complicate its handling, storage, and energy conversion. To overcome these obstacles, pre-treatment processes are essential to enhance the fuel characteristics of biomass, making it more suitable for efficient energy production. One highly effective pre-treatment method is torrefaction, a mild thermochemical process performed at temperatures between 200°C and 300°C in an inert atmosphere[17]. Torrefaction is a crucial

pre-treatment process that transforms raw biomass into a more efficient and effective fuel source. By improving the physical and chemical properties of biomass, torrefaction addresses many of the challenges associated with raw biomass, making it a more viable option for sustainable energy production. This process significantly improves the energy density, grindability, and combustion characteristics of biomass[18]–[20]. During torrefaction, biomass undergoes partial thermal decomposition, which removes moisture and volatile compounds. This transformation increases the carbon content and energy density of the biomass, creating a more energy-rich and hydrophobic material that is easier to grind and store[21]–[23]. Therefore, more research is necessary to determine the optimal conditions for obtaining materials with the best possible properties and making capable of producing biochar suitable for power generation. Additionally, more studies are needed on the grindability characteristics of torrefied PKS, including an assessment of its porosity for potential use in combustion or co-combustion processes. Improved grindability results in finer particles, which are crucial for efficient combustion and gasification processes. Junga et.al [24]studied the effects of temperature and residence time on the torrefaction of palm kernel shell. They found that the grindability of the torrefied material improved with increasing temperature and residence time. Ivanovsky et al. [25] also concluded that the increasing the temperature of torrefaction significantly enhances the heating value and grindability compared to raw materials. Enhanced combustion characteristics of torrefied biomass leads to more efficient and complete burning, reducing emissions and increasing energy output [26]–[28]. Torrefaction also increases the porosity of biomass[29]–[31]. The removal of volatiles creates micro-pores and channels within the material, enhancing its surface area. This can be beneficial for applications requiring high reactivity, such as combustion and gasification. As the porosity increases, the biomass becomes more brittle and easier to grind[32], [33]. This is advantageous for processes that require fine biomass particles, such as co-firing with coal in power plants.

Despite these benefits, torrefaction alone may not fully address all the challenges of biomass utilisation. The uniformity and efficiency of the process can vary depending on the type of biomass and the specific conditions under which it is conducted. Hence, innovative approaches are needed to further optimise the properties of torrefied biomass, making it an even more viable and effective renewable energy source [34], [35]. Recent advancements in pre-treatment technologies highlight the potential of microwave preheating as a complementary process to torrefaction. Microwave preheating offers rapid and uniform heating, improving control over the torrefaction process and ensuring more efficient energy transfer[36]–[40]. This technique can possibly enhance the uniformity and efficiency of torrefaction, resulting in biomass with superior grindability and porosity—the key properties for its use as an energy source[35], [41], [42]. Grindability, which determines how easily biomass can be pulverised, directly impacts the efficiency of downstream processes such as combustion and gasification[4], [43], [44]. Meanwhile, porosity influences the material's surface area, permeability, and reactivity, all of which are critical for effective combustion[45][43], [45]–[47]. By optimising these parameters through the combination of microwave preheating and torrefaction, it supposes to enhance the overall performance and sustainability of biomass as a renewable energy source. Advanced characterisation techniques like mercury intrusion porosimeter and scanning electron microscopy (SEM) provide detailed insights into the structural changes induced by these processes. These techniques allow researchers to analyse the improvements in biomass properties at a microscopic level, ensuring a comprehensive understanding of how microwave preheating and torrefaction enhance biomass performance[44], [48]. This detailed knowledge is essential for further refining the processes and developing even more efficient and sustainable methods for biomass utilization.

The primary objective of this study is to investigate the impact of microwave preheating and torrefaction conditions-specially temperatures of 200°C, 350°C, and 300°C, and residence times of 30 minutes-on biochar derived from palm kernel shell (PKS) and coconut shell (CS). The research focuses on evaluating the grindability, porosity, energy density enhancement and energy yield of the torrefied products. Currently, there is limited literature on the grindability and porosity of torrefied PKS, particularly in relation to their pretreatment with microwave heating. This study aims to fill that gap by providing comprehensive insights into the effect of microwave preheating on these critical properties.

2. Method

2.1. Samples

Palm Kernel Shells is chosen for this study due to their abundance, high energy content, and potential for sustainable energy production. The coconut and palm kernel shells were initially prepared by cleaning, drying them for 3-4 days, and cutting them to a uniform size of around 10-12 mm to make them suitable for torrefaction reactor. To ensure uniformity of moisture content, the samples were further dried in an electric oven at 105°C for 12 hours[49]. Subsequently, these samples were stored within sealed glass containers until the day of the experiments. The properties of raw materials used in this study can be seen in Table 1.

Table 1. Characteristics of raw samples material

Analysis	Properties	Value
Proximate Analysis	Moisture content (MC)	4.22
	Volatile matter (VM)	69.32
	Ash content (A)	3.25
	Fixed carbon (FC)*	22.21
Ultimate Analysis	C	48.65
	H	7.13
	O*	43.21
	N	0.91
Heating Value (MJ/kg)	HHV	17.14

* by different

2.2. Preheating and Torrefaction operations

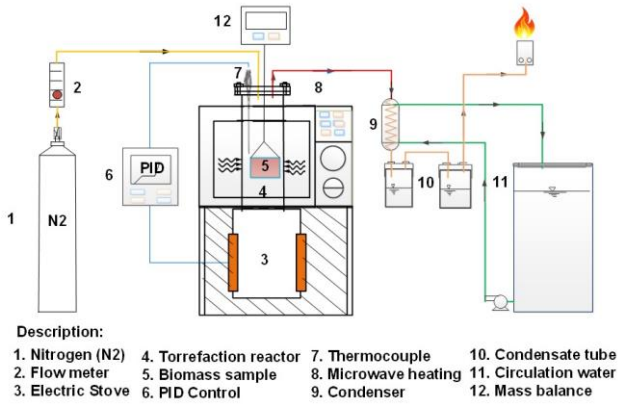

Fig.1. Schematic view of the experimental apparatus.

The torrefaction process was conducted in a vertical bench-scale tubular reactor, utilizing a 1000 mL borosilicate glass vessel with an internal diameter of 46 mm and a length of 400 mm. Layout of torrefaction experiment can be seen in Fig.1. Microwave (MW) preheating is performed using a laboratory-scale microwave oven with adjustable power settings detailed in previous paper [50]. In this study, 40 grams of PKS and CS samples were weighed and placed inside reactor. In order to prevent oxidation during the torrefaction process, nitrogen gas was flowed into the muffle reactor for 10 minutes before conducting the experimental. The key parameters such as microwave power and exposure time of the samples, were varied to evaluate their impact on Torrefaction efficiency [51]. Initially, the samples are exposed to microwave radiation at power levels of 360W, 540W, and 720W, with exposure times of 10 minutes for each power level. The torrefaction process is then continued at temperatures of 200°C, 250°C, and 300°C, as detailed in Table 2. During the torrefaction process, samples were continuously monitored to ensure consistent heating and to observe any changes in physical properties.

After the experiment was completed, the mass of the torrefied product was measured using precision mass balances. The torrefied samples were then saved for further analysis, focusing specifically on their grindability and porosity. This subsequent analysis aims to evaluate the effectiveness of the torrefaction process and to determine any improvements in the material properties. Additionally, the impact of varying microwave power levels and exposure times on the efficiency and quality of the torrefied products will be assessed. This analysis will help identify the optimal preheating conditions, ensuring the most effective enhancement of the biomass properties. The grindability of the torrefied samples will be tested to determine how easily they can be pulverized, which is crucial for their application in combustion and gasification processes. Improved grindability results in finer particles, facilitating more efficient and complete burning[52]. Porosity will also be analysed to understand changes in the material's surface area, permeability, and reactivity. Higher porosity can enhance the biomass's ability to interact with gases during combustion, leading to better energy conversion[44], [53].

Table 2. Experimental parameters

Parameter settings	Values
Microwave (MW) heating power	360W, 540W, 720W
Microwave heating times	10 minutes
Torrefaction temperature	200ºC, 250ºC, 300ºC
Torrefaction time	30 minutes

The results can provide insights into optimizing the torrefaction process for coconut and palm kernel shells, enhancing their utility in several energy applications.

2.3. Psychochemical analysis of solid products

The properties of torrefied solid products were examined using proximate and ultimate analysis. Proximate analysis was conducted for both raw and torrefied material, encompassing measurement for moisture content (MC), ash (A), volatiles matter (VM), and fixed carbon (FC) using ASTM standards E871-82, D1102-84, and E872-82, respectively. The ultimate analysis provides the composition of the biomass in wt.% of carbon, hydrogen and oxygen (the major components) as well as sulphur and nitrogen. Elemental analysis of solid products was also determined using LECO CHN628. Higher Heating Value (HHV) was determined on the basis of thermal energy generated by complete combustion of the sample in a constant pressure chamber. The calorific value of the products were analyzed using ASTM D2382-88.

Furthermore, the torrefied products were analysed by Thermogravimetric analysis (TGA), Derivative Thermogravimetric analysis (DTG) and Scanning Electron Microscopy (SEM). TGA used to provide the weight of a sample changes as the temperature increases, while DTG used to highlight the rate of weight change. SEM analysis the surface morphology and chemical changes that occur during the preheating and torrefaction processes. Image J was used to further analyse the pores distribution in SEM pictures.

2.4. Grinding test

The torrefied products were also characterized to evaluate their grindability. Measuring the grindability of biomass involves assessing how easily the biomass can be ground into smaller particles. This is important for processes such as pelletizing, combustion, and gasification of solid fuel. Grindability of the torrefied biomass was measured using a milling tester ABB CE type HP 963 that usually used for bituminous coal grinding test. This machine consists a bowl with three grinding rollers. Particle sizes produced were classified into two categories: particles passing through a 10 mm sieve and particles passing through a 5 mm sieve.

2.5. Porosity test

Porosity measured as a percentage of volume is the measure of the empty spaces or voids within a material relative to its total volume. It indicates how much of the material's volume is not occupied by solid matter but by air or liquid. Porosity of the torrefied biomass was analyzed using porosity meter (POPG-200TMUnit) to determine pore volume available

inside the torrefied products. High porosity usually indicate that the material has a lot of space to hold air or liquid.

2.6. Product analysis

The performance of biomass torrefaction can also be assessed using parameters such as mass yield and energy yield. Mass yield indicates the proportion of the initial biomass that remains in the solid product after the torrefaction process. It indicates the efficiency of the process in preserving the solid biomass fraction. It can be calculated as follow[54].

$$MY = \left(\frac{m_f}{m_i}\right) \times 100\% \quad (1)$$

Where: m_f is the mass of torrefied biomass (kg) and m_i is the initial mass of raw biomass (kg). A higher mass yield indicates that a larger proportion of the original biomass mass is retained after torrefaction, which is generally desirable as it signifies less loss of biomass during the process.

Enhancing the energy density of torrefaction products is another crucial parameter to measures the amount of energy released when a unit mass of the torrefied product is burned. Energy density is related to terms like specific energy, calorific value, and heating value. In torrefied biomass, energy density enhancement refers to the increase in energy stored within a given volume or mass of biomass after the torrefaction process. This factor is commonly used to express the change in calorific value or combustion efficiency between torrefied and raw biomass, and expressed as energy density enhancement (EDE). It can be calculated using the following formula [54].

$$EDE = \frac{HHV_f - HHV_i}{HHV_i} \times 100\% \quad (2)$$

Energy yield (EY) refers to the amount of energy contained within the torrefied biomass compared to the raw biomass. It takes into account changes in energy content due to the removal of moisture and volatile components during torrefaction. It is written as [55]:

$$EY = \left(\frac{m_f}{m_i}\right) \times \frac{HHV_f}{HHV_{\mathrm{i}}} x100\% \quad (3)$$

With HHV_f represents the higher heating value of torrefied biomass (MJ/kg) and HHV_{i} represents the higher heating value of raw biomass (MJ/kg).

Higher energy yield indicates better efficiency in retaining or enhancing the energy content per unit mass of biomass after torrefaction, which is crucial for evaluating the economic and environmental benefits of biomass torrefaction processes.

To assess the suitability of torrefied biomass as a high-quality solid biofuel, it is essential to consider parameters such as Fuel Ratio (FR), Combustible Index (CI), and Volatile Ignitability (VI) [56]. Combustible Index or Flammability Index, quantifies the combustibility and flammability characteristics of a material. This index quantifies the combustibility and flammability characteristics of a material. This index is crucial for assessing fire hazards and determining appropriate safety measures. Volatile Ignitability is another important parameter, referring to the ease with which volatile substances or materials that release flammable vapours can ignite. These volatile substances are typically characterized by their ability to vaporize at relatively low temperatures, producing vapours that can easily mix with air and form flammable or explosive mixtures. These parameters can be calculated as follows [56]:

$$R = \left(\frac{FC}{VM}\right) \quad (4)$$

$$CI = \left(\frac{HHV_f}{FR}\right) \times \frac{1}{105} x(115 - A) \quad (5)$$

$$VI = \left(\frac{HHV - 0.338FC}{VM + MC}\right) \times 100 \quad (6)$$

Where: FR is Fuel ratio (-), CI is Combustible index (-), VI is volatile ignitability (MJ/kg), FC is Fix carbon (-), MC is Moisture content (%), A is ash (%), and VM is volatile matter (%).

3. Results and Discussion

The chemical and physical characteristics of torrefied PKS are presented in **Tables 3** and **4**. It is evident that increasing the microwave power level and torrefaction temperature enhances the properties of the torrefied product. Specifically, moisture content and volatile matter decrease, while fixed carbon increases, leading to an improved calorific value compared to the raw material. At a torrefaction temperature of 200°C, the volatile matter decreased from 69.32% at raw to average of 55.1% while fixed carbon increased from 22.21% to 29.3%. A similar trend is observed at temperatures of 250°C and 300°C, where the volatile matter decreased by approximately 35% and 47%, respectively. As the volatile components escape from the biomass, the fixed carbon content increases, resulting in a material with higher energy density.

Fig.2 shows the increase in energy density as both the temperature and power level rise. The enhancement of energy density reaches its optimum at a temperature of 300°C and a power level of 720 W. It can also be observed that increasing the power level of microwave heating improves energy density enhancement, although the improvement is not significant. The maximum energy density enhancements at temperatures of 200°C, 250°C, and 300°C were 22.8%, 32.7%, and 38.8%, respectively. This indicates that higher power levels and torrefaction temperatures have the potential to enhance the energy density of the torrefied product.

Fig. 3 illustrates the energy yield as a percentage at different torrefaction temperatures (200°C, 250°C, and 300°C) for three microwave power levels (360 W, 540 W, and 720 W). The data shows a significant decrease in energy yield as the torrefaction temperature increases from 200°C to 300°C, indicating that higher temperatures reduce energy yield efficiency. This phenomenon is likely due to a substantial reduction in mass yield (as in table 4), even though the calorific value may increase. It reveals that torrefaction temperature has a more significant impact on energy yield

Tabel 3. Proximate analysis of torrefied PKS

Microwave Power (Watt)	Torre-faction Temp.(°C)	MC (%)	VM (%)	A (%)	FC (%)	Calorific Value (MJ/kg)
360		4.73	56.8	1.2	39.2	20.63
540	200	4.36	55.15	1.2	39.29	21.32
720		4.12	53.36	1.1	41.42	20.76
360		4.35	54.38	1.2	40.07	22.18
540	250	4.12	52.65	1.1	42.13	22.35
720		3.76	46.75	1.3	48.19	22.75
360		4.24	51.78	1.1	42.88	24.14
540	300	3.83	50.12	1.2	44.85	23.69
720		3.47	37.6	1.2	57.73	24.15

Table 4. Elemental analysis of Torrefied PKS

Microwave Power (W)	Torre-faction Temp.(°C)	C (%)	H (%)	O (%)	N (%)	Mass yield (%)
360		50.03	6.61	43.36	0.56	87.45
540	200	49.11	6.54	44.35	0.51	85.22
720		54.94	6.17	38.89	0.55	86.62
360		58.6	5.66	35.74	0.55	66.73
540	250	60.84	5.41	33.75	0.54	67.24
720		60.04	5.54	34.42	0.55	68.13
360		66.21	5.25	28.54	0.57	58.12
540	300	63.94	5.39	30.67	0.53	57.15
720		64.18	5.54	30.28	0.49	58.37

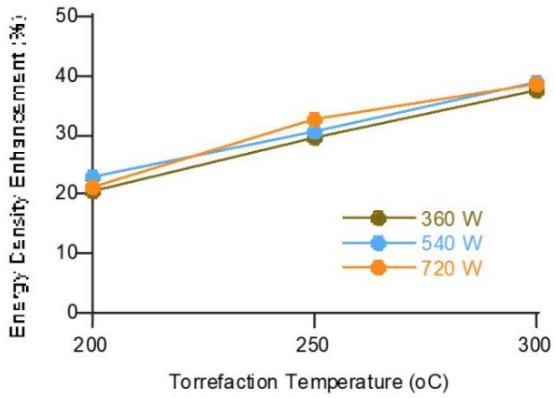

Fig. 2. Energy density enhancement of PKS at different torrefaction temperature.

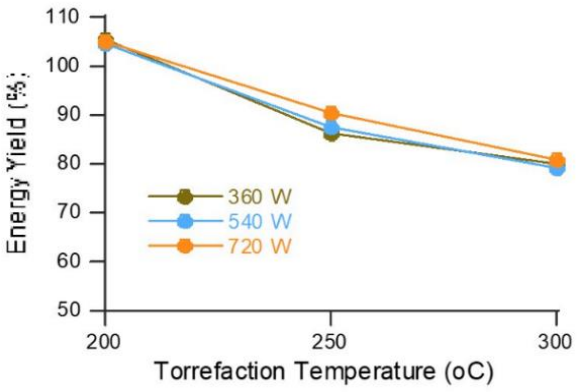

Fig. 3. Energy Yield of the torrefied PKS at different power and torrefaction temperature.

than the microwave power level.

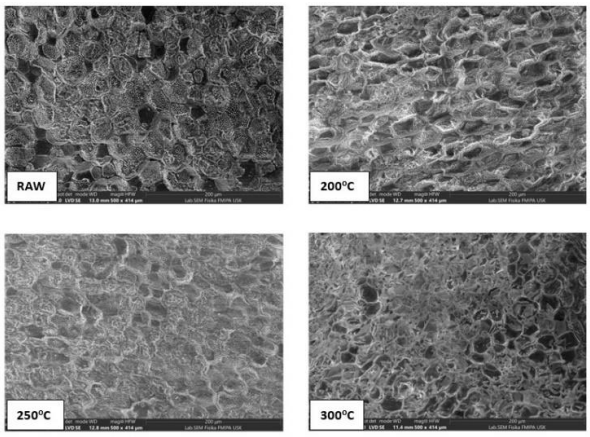

Fig. 4. Surface morphology of raw and the product of PKS at different torrefaction temperature

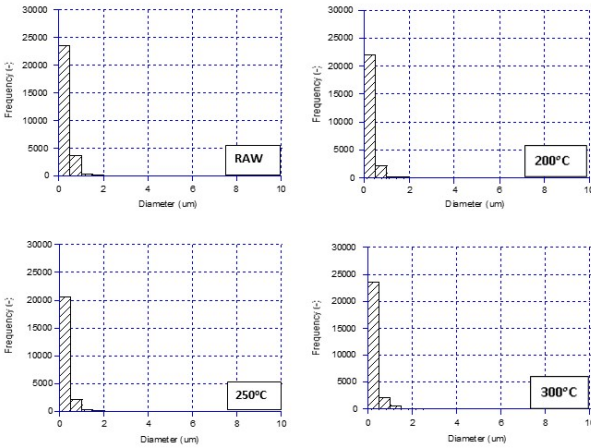

Fig. 5. Particles distribution of pores inside the raw and torrefied products (from SEM analysis using image J).

Table 5. Porosity analysis of raw and torrefied product of PKS

Microwave Power (Watt)	Torrefaction Temperature (°C)	Porosity (%)
RAW	-	28.42%
360		31.64
450	200	32.03
720		33.47
360		32.24
450	250	32.63
720		35.91
360		34.43
450	300	36.55
720		37.62

Fig. 4. displays the surface morphology of solid products at different temperature torrefaction. The raw material shows a compact and uniform structure with little to no signs of decomposition or structural damage. In 200°C, there is a noticeable reduction in the density of the structure, with some pores and slight deformation visible, indicating the initial stages of thermal degradation. In 250°C, the material shows further degradation, with larger pores and more pronounced deformation of the cellular walls, suggesting

increased mass loss and structural breakdown. In 300ºC, the structure is highly porous, with significant collapse of the cellular framework. This indicates severe thermal decomposition and substantial mass loss. Higher torrefaction temperatures result in increased porosity, indicating greater mass loss and structural breakdown.

Fig. 5 Shows the correlation between temperature treatment and pores generate inside the solid products. It can be seen that as the temperature increases from RAW to 300°C, there is a noticeable trend of decreasing frequency of small pores, indicating potential changes in the material's porosity structure due to the heat treatment. Across all temperature conditions, the majority of pores are concentrated around the 0.5 µm diameter range. It implies that the material inherently has a significant number of small pores, and this characteristic is somewhat retained even after thermal treatment. It can be seen also that there is a clear reduction in the frequency of these small pores as the temperature increases. The RAW sample shows the highest frequency of pores, while the 300°C sample shows the lowest. This suggests that higher temperatures might be causing some pore collapse or merging, resulting in a decrease in the overall number of detectable pores. The consistent decrease in frequency of pores with increasing temperature suggests that thermal treatment impacts the microstructure of the material. The treatment might be causing densification or sintering effects, which can reduce the total pore volume and number. The graphs illustrate that while the basic pore size distribution (majority around 0.5 µm) is maintained, the frequency of these pores decreases with increasing temperature, indicating a potential densification effect due to thermal processing. In all conditions, there are very few pores with diameters greater than 1 µm. This indicates that the torrefaction process does not significantly generate large pores, but rather affects the existing small pore structure.

Table 5. shows the lab analysis of porosity for untreated (raw) and torrefied PKS. It is revealed that torrefaction temperature and power level of microwave preheating improve the porosity of torrefied products. It is same trend provided in the Fig.4 and 5. In the table it can also be seen that porosity torrefied at 200ºC can increase from 28.4% in raw to an average of 32.4% in torrefied PKS whiles for the temperature of 250ºC and 300ºC the porosity increases around 33.6% and 36.2% respectively. The higher the temperature tend to increase the pores in the PKS and leads to improve the combustion system[53]. This can be affected by the escaping of moisture and volatile gases from samples during microwave preheating and torrefaction.

Fig. 6 and **Fig. 7** illustrate the DTA and DTG analysis of different power level of microwave at torrefaction temperature of 300ºC. These graphs highlight the importance of optimizing these parameters to enhance fuel properties. Different power levels can affect the rate and extent of biomass decomposition. The DTA curves show the temperature difference between the sample and a reference as the temperature increases. An initial temperature difference up to around 100°C likely corresponds to moisture evaporation. Significant temperature changes begin around 200°C and continue up to about 350°C, indicating thermal events like decomposition. Higher power levels may

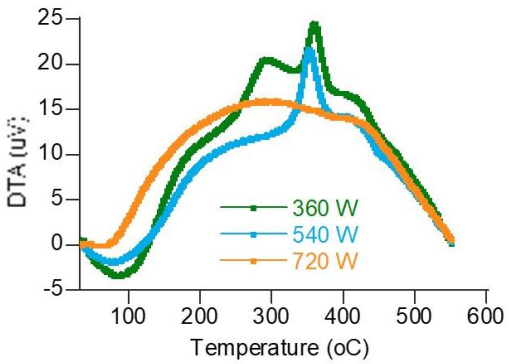

Fig.6. DTA analysis of torrefied PKS at 300ºC)

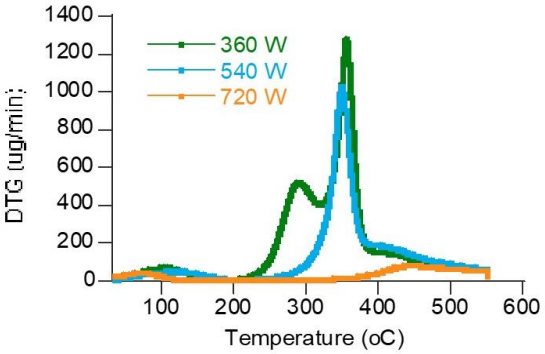

Fig.7. DTG analysis of torrefied PKS at 300ºC)

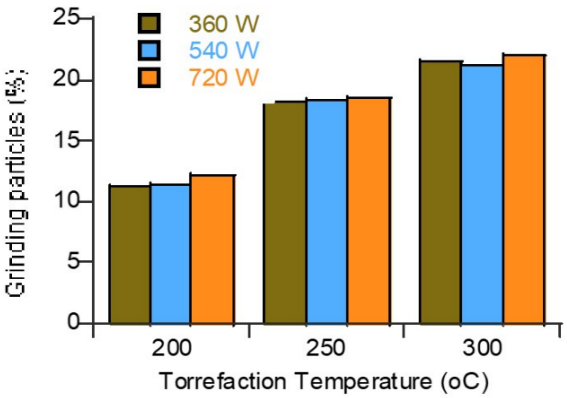

Fig.8. Grindability of the torrefied PKS at different power and temperature

lead to more rapid and complete decomposition, as indicated by the sharper DTG peaks. Prominent DTG peaks around 250°C across all graphs indicate the primary decomposition phase.

The graph in **Fig. 8** shows the percentage of grinding particles less than 5 mm in size at different torrefaction temperatures (200°C, 250°C, and 300°C) for three different power levels: 360 W, 540 W, and 720 W. The percentage of grinding particles pass through the 5 mm sieve increases as the torrefaction temperature increases from 200°C to 300°C. This reveal that higher temperatures make the biomass more brittle and easier to grind into smaller particles. However, the power levels (360 W, 540 W, 720 W) do not significantly affect the percentage of grinding particles. This suggests that, within the examined range, power level has a minimal impact on the grindability of the torrefied biomass. This

might be due to the short resident time (10 minutes) of exposure to the microwave energy.

Table 6. Distribution of particle size of raw and torrefied product at 720 W

Particle size	Raw (%)	Torrefaction Temperatur at MW 720 W		
		200°C	250°C	300°C
>15	0	0	0	0
10-5	4.50	0	0	0
5-2.5	1.20	5.60	4.56	2.15
2.5-1	0.20	2.10	5.22	4.75
1-0.5	0.10	3.50	2.30	2.80
<0.5	0	2.10	6.50	10.40

In the **Table 6**, it can be seen the distribution of grinding particles for torrefied samples. The higher the torrefaction temperature, the higher the number of particles produced in different sieve sizes. This indicates that torrefaction at elevated temperatures not only causes more extensive breakdown of the material but also results in finer particle sizes. As the temperature increases, the structural integrity of the material diminishes, leading to more fragmentation during grinding. Consequently, samples torrefied at higher temperatures exhibit a greater proportion of smaller particles, as evidenced by the increased numbers found in the finer sieve fractions.

Fig. 9. provides the information of combustion index of material torrefied in this study. Based on the formula proposed by Singh et.al,2020 [56], it can be seen the combustion index of the torrefied products. For each power level, the CI generally increases with higher torrefaction temperatures, peaking at 300°C. At lower temperatures (200°C and 250°C), the CI increases with higher power levels. However, at 300°C, the highest Combustible Index is observed at 360 W, while it decreases significantly for 720 W. This suggests that there might be an optimal torrefaction temperature and power level for maximizing the combustible properties of biomass. The significant drop of CI at 720°C could be due to over-heating on the product during torrefaction process.

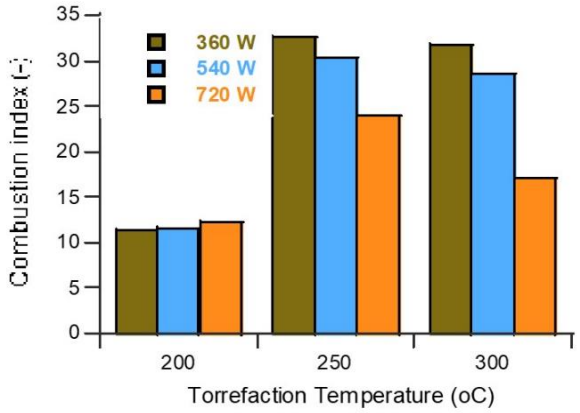

Fig. 9. Combustion index of torrefied PKS at different power of microwave and torrefaction temperature

Excessive energy input at such a high temperature might lead to undesirable effects, such as excessive breakdown of biomass structure, increased formation of non-combustible residues, or even partial combustion. Over-torrefaction can degrade the cellulose, hemicellulose, and lignin in the biomass and lead to reduce the availability of combustible material. This phenomenon might also cause increased loss of energy-rich components, leading to a lower combustible index on the torrefied products.

4. Conclusion

The study demonstrates that microwave preheating and torrefaction significantly enhance the grindability and porosity of palm kernel shell (PKS), making it a more viable feedstock for sustainable energy production. Higher torrefaction temperatures improve the energy density and yield of the PKS, even though with diminishing returns at elevated temperatures due to increased mass loss. The SEM analysis reveals that increased torrefaction temperatures lead to greater structural degradation and porosity, facilitating easier grinding and finer particle sizes. This improvement in grindability and porosity contributes to more efficient energy conversion processes. Overall, the combined use of microwave preheating and torrefaction optimizes the physical properties of PKS, thereby supporting its application as a renewable and efficient energy source. These enhancements can also contribute to more effective and cleaner energy production.

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Author contributions

LKM: Conceptualization, Methodology, Formal Analysis, Writing—Original Draft, **RRS:** Formal analysis, supervision, writing—reviewing and editing, **LP and M:** Visualization, Investigation, Writing-Reviewing and Editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

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