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TORREFACTION OF PALM KERNEL SHELL AND RICE HUSK FOR ENHANCED SOLID FUEL ENERGY PERFORMANCE

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ABSTRACT

The present study investigated the effect of torrefaction on the characteristics of rice husk (RH) and palm kernel shell (PKS) under varying conditions, specifically temperatures ranging from 200-300 °C and residence times between 35-60 mins in an inert environment. The results showed that higher temperatures and longer residence times increased the fixed carbon content, ash content, and moisture content of the biomass, all of which improved the torrefied biomass's high heating value (HHV). The optimum HHV achieved for the torrefied PKS was 22.89 MJ/kg, which was 17.3% higher than 18.93 MJ/kg for RH at 300 ^{0}C, 60 minutes. This treatment also resulted in subsequent reductions in O/C ratio of PKS and RH by 42.1% and 40% respectivey, from 1.14 to 0.66 and 0.94 to 0.54, and H/C ratio from 1.45 to 0.84 and 1.13 to 0.84 PKS rand RH espectively. The torrefied PKS showed more enhancement than RH under the same condition. The energy yield and mass yield decrease with an increase in the torrefaction temperature and residence time. The FTIR spectra showed a progressive loss of hydroxyl, carbonyl and C–O functionalities and the appearance of aromatic C=C bonds, indicating the formation of the biochar. Thus, this research presented torrefaction as a promising approach to the enhancement of biomass characteristic and torrefied solid fuel as competitive alternatives to traditional biomass resources in the biofuel industry, thereby promoting sustainable energy practices.

Keywords: Torrefaction, Biomass, Solid fuel, Higher heating value, Enhancement factor

INTRODUCTION

The rapid development of human society, population growth, industrialization has been accompanied by the massive consumption (over-exploitation) of fossil fuels such as coal, oil and natural gas, meanwhile generating and releasing large amounts of carbon (iv)oxide (CO_2) leading to environmental problems and posing a direct threat to human survival (Sun *et al*., 2023; Mignogna *et al*., 2024). This is of global concern and has led to the continuous search for alternative energy sources (Mignogna *et al*., 2024). Therefore, the concept of green, renewable and cleaner energy processes that could potentially stimulate progress toward climate neutrality, paving the way for sustainability is much needed. Thus, there has been a significant increase in the use of renewable energy sources like wind, solar, biomass, and geothermal energy (Gasparotto *et al*., 2020). By using biomass, renewable non-fossil raw materials in the production of energy, environmental sustainability goals can be met.

Biomass is the fourth largest resource after coal, oil and natural gas. It accounts for about 14% of total energy consumption and 38% of energy consumption in emerging countries (Siwal *et al*., 2022). It is an ideal alternative to traditional fossil fuels because it is abundant, renewable, carbon neutral and of low-pollution nature (Liu *et al*., 2022, Kimpa *et al.*, 2024). The key to biomass energy utilization is the conversion of biomass into different forms of energy carriers as well as by-products through conversion processes (Ahmad *et al*., 2023; Onwudili *et al*., 2023).

However, the use of raw biomass for energy production and thermochemical conversions is limited by some undesirable properties of biomass, such as low bulk density, low energy density, hydrophilic character, low calorific value (CV), high moisture content, high oxygen content, poor grindability, as well as thermal instability, which resulted from high oxygen/carbon (O/C) ratio (Cheng *et al*., 2022; Ahmad *et al*., 2023). These characteristics make it difficult to store, handle and transport biomass for its conversion into energy (Torres *et al*., 2023). Therefore, pretreatment of biomass feedstock by torrefaction should be carried out prior to thermochemical conversion of the biomass (Chen *et al*., 2021).

Torrefaction, a thermal pretreatment is the process of gently heating biomass in the temperature range of 200–300 °C in an inert or oxygen-deficient environment (Tumuluru *et al*., 2021). This process has gained prominence in industries as an efficient method for upgrading biomass materials, enhancing their energy content, physical characteristics, chemical properties and increasing its efficiency during thermal conversion (Rashwan *et al*., 2025). Moisture and several volatile organic molecules evaporate from the biomass during torrefaction and the main product obtained is a homogenous solid, with a higher energy content and less moisture, known as torrefied biomass, biochar, or charcoal (Khairy *et al*., 2024).

Torrefied biomass characteristics are influenced by several process parameters, including temperature, residence time, particle size, biomass type and carrier gas. Previous studies on torrefaction have reported the influence of the operating conditions on the characteristics of torrefied fuel such as mass yield, energy yield, energy density, as well as fuel properties of the torrefied product, including proximate and ultimate analysis and HHV (Phengpom *et al*., 2023; Khairy *et al*., 2024) reported an increased HHV from the torrefaction of sesame stalks and bean husk as temperature and time increased, with the highest HHV been obtained at 275 °C and 30 min. The HHV of wheat straw increased from 13.86 to 19.41 MJ kg^{-1} with increase in temperature with the optimum torrefaction conditions being 287 ◦C and 20 minutes (Torres *et al.*, 2023). Phengpom *et al*. (2023) observed that the physicochemical and fuel properties of the obtained biochar were improved compared with the raw biomass in the

torrefaction of betel nutshells as the atomic O/C ratio was reduced from 1.38 to 0.8 with an increase in temperature and residence time. The optimum operating temperature of 300 °C and a residence time of 60 minutes were also reported. Most of the research work on torrefaction process focused on the property changes of biomass.

Identifying the role of operating parameters during torrefaction is helpful for the quality improvement of the products and process optimization (Chew *et al*., 2020; Sun *et al*., 2023). Several studies have been conducted on biomass from only oil palm or rice biomass source individually or in combination such as EFB, PKS, RH and rice straw (Sukiran *et al*., 2020; Ahmad *et al*., 2021; Chen *et al*., 2021; Khamwichit *et al*., 2024). However, very few studies have discussed the correlation and the differences in the torrefaction behavior of PKS and RH under the same condition from the experimental perspective. Therefore, this study focused on analyzing the effect of temperature and residence time on the physical characteristics of the torrefied product using the physicochemical properties, fibre compositions, SEM and FTIR and to comparatively study the torrefaction of PKS and rice husk by characterization of the solid products under different torrefaction severities

MATERIALS AND METHODS

Materials Preparation

Palm Kernel Shell (PKS) was procured from a local palm oil mill while Rice Husk (RH) was collected from a local rice mill in Ogo-Oluwa Local Government Area of Ogbomoso, Oyo State, South Western Nigeria. Palm Kernel Shell (PKS) was washed with deionized water to remove dust. The biomass materials (PKS and RH) were dried at 105 ºC to reduce moisture content. It was then crushed using a milling machine and sieved using a sieve shaking machine (RETSCH type AS200 digit, Germany). It was equipped with 0.5– 4mm filter mesh to get different particle sizes and the biomass with particle size 2mm fraction was selected. These samples were stored in air-tight bags in a dark place at room temperature prior to further experiment

Characterization of Raw and Torrefied Biomass

Physicochemical properties of the selected biomass that were determined include the proximate analysis, ultimate analysis and higher heating value. Analytical characterization carried out include surface chemistry and morphology, with the use of Fourier Transform Infrared Spectrometer (FTIR) analysis and Scanning Electron Microscopy (SEM) analysis while the compositional (fibre) analysis was carried out to determine the lignocellulosic properties of the biomass. These analyses were carried out before and after torrefaction experiments.

Proximate Analysis

The proximate analysis was performed in compliance with (ASTM D 3173-03) to determine the moisture content (MC), volatile matter (VM), ash content (AC), and fixed carbon contents (FC) of the samples.

Ultimate Analysis

The ultimate analysis of the biomass typically involves the determination of the percentage of Carbon (C), Hydrogen (C), Oxygen (O), Nitrogen (N) and Sulphur (S). These were determined according to American Society for Testing and Materials (ASTM) standards D 3174-76 for agrowaste using LECO CHN 2000 Elemental Analyzer.

Determination of Higher Heating Value (HHV)

The heating value of the sample was examined using a Bomb Calorimeter (The Cal 2k-Eco Calorimeter), and the procedure was in accordance with the ASTM E 711-87 (2004).

Lignocellulose Analysis of Biomass

Lignocellulose analysis was used to determine the percentage composition of lignin, hemicellulose and cellulose in the biomass following the procedure of Khamwichit *et al*., (2024). To extract the lignocelluloses from the biomass, 5 g of dried samples was added to 80 cm^3 of acetone. The acetone extraction using a Soxhlet extractor (Foss SoxtecTM 2050, Hillerød, Denmark) was carried out at 90 ◦C for 1 h, followed by rinsing with the acetone for 30 min at room temperature. The insoluble solids was collected and dried in a hot-air oven at 105 ◦C for 24 h, left to cool in a desiccator, and then weighed. The extractable contents E (%) of the biomass was calculated using equations 1

$$E\ (\%) = \left(\frac{(W_0 - W_1)}{W_0}\right) x\ 100 \quad (1)$$

where,

W_0 and W_1 is the dry weight of torrefied biomass before and after extraction, respectively. The hemicellulose content, H (%) was determined using equations 2

$$H\ (\%) = \left(\frac{(W_1 - W_2)}{W_1}\right)\ x\ 100 \quad (2)$$

where W_2 is the dry weight after the alkali treatment.

For lignin content calculation, the acid-insoluble lignin content, L (%), of the sample was calculated using equations 3

$$L\ (\%) = \left(\frac{W_4}{W_3}\right)\ x\ 100 \quad (3)$$

where W_3 is the weight of the sample before treatment and W_4 is the weight of the solids recovered after the treatment.

Based on the acetone-extracted torrefied biomass, the cellulose content, C (%), was calculated from the values of C and H obtained by difference using equations 4:

$$C\ (\%) = 100 - (\ H(\%) + \ L\ (\%) \quad (4)$$

Fourier Transform Infrared (FTIR) Analysis

FTIR spectra of the samples was analyzed to assess the functional groups of the raw and torrefied solid products for a better understanding of the effect of torrefaction on the chemical structure of the biomass. For this, 1g of dried sample was used to prepare a KBr disk for the test. The FTIR spectra of the samples was examined in an ATR-FTIR spectrometer (Model Tensor 27; Bruker, Munich, Germany) within the wavelength range of 500–4000 cm^{-1} with a step of 2 cm^{-1} (Premchand *et al*., 2023).

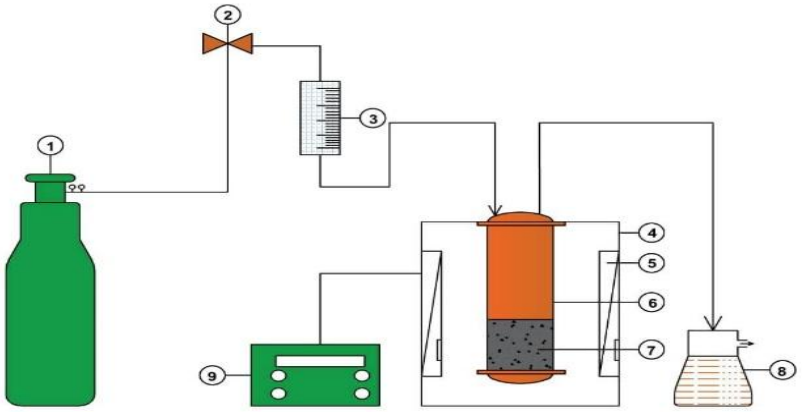
Determination of the Surface Morphology using Scanning Electron Microscopy

SEM, Hitachi SU 3500 scanning microscope, Tokyo, Japan) was used to study the morphological structure, potentially conveying insights into how the torrefaction process influences the structural alterations of the biomass at varying temperatures.

Experimental Procedure

Torrefaction process of biomass feed stocks was conducted in a fixed bed reactor. The reactor consists of a 30cm long steel tube, 3.5 cm diameter and an internal diameter of 2.5 cm in which biomass particles was deposited. The reactor is surrounded by an electrical furnace. Approximately 20 g of the feed stock with particle size 2 mm was placed in the reactor and heated up to the target torrefaction temperatures from 200 to 300℃ at a heating rate of 20 ℃/min at varying residence times from 35 to 60 minutes. The target temperature

was maintained for the set times and high purity (99.999 %) Nitrogen gas, N_2, from a gas cylinder controlled by a flow controller was fed into the reactor at a fixed flow rate of 150 ml/min to create an inert environment in the reactor by displacing oxygen and volatile compounds. (Phengpom *et al*., 2023; Pimsamarn *et al*., 2024). At the top of the reactor, a hard board was used to prevent air from entering the reactor by natural convection effects. The reactor was moved out of the furnace when the residence time is complete and the torrefied solid product was taken out of the steel tube after cooling to the room temperature (Xu *et al*., 2024). A schematic diagram of the torrefaction process is shown in figure 1. The physical appearance or color changes of the raw and torrefied biomass was observed. The torrefied biomass was placed in a desiccator for 30 minutes, weighed using a high-precision digital mass balance and stored in a zip-lock bag for further analysis. Each experiment was repeated at least 2 times to ensure accuracy.



1. Nitrogen Gas Cylinder, 2. Needle Valve, 3. Gas Flow meter, 4. Furnace, 5. Electric Heater, 6. Torrefaction Reactor, 7. Biomass Feedstock, 8. Filter Flask, 9. Thermocouple
Figure 1: Schematic Diagram of the Experimental Setup for Torrefaction

Yield of Torrefied Biomass Solid Products

The yield of the torrefied solid products (biochar) obtained at different temperatures and time were determined using equations 5, 6 and 7 below

Mass Yield

Mass yield" refers to the proportion of the mass of the torrefed biomass to the mass of the raw biomass. It is the ratio of the mass of the solid material after the torrefaction process to the initial mass of the same material before the process (Rashwan *et al*., 2025). The mass yield was calculated using Equation 5 (Awang *et al*., 2019).

$$Mass\ yield\ of\ solid\ product\ = \frac{mass\ of\ torrefied\ solid\ \ products\ (g)}{mass\ of\ raw\ biomass\ (g)}\ x\ 100 \qquad (5)$$

Energy Yield

The energy yield is the ratio of the torrefied solid's energy to that of the raw biomass. It is an important parameter for analyzing the torrefaction process. It is calculated using equation 6 as follows:

$$Energy\ yield\ of\ product = Mass\ yield\ (\%)\ x\ \frac{HHV\ of\ torrefied\ produt\ (\ (MJ/kg)}{HHV\ of\ raw\ biomass\ (\ (MJ/kg)\ )}\ x\ 100 \qquad (6)$$

Enhancement Factor

Enhancement factor is the ratio of the improved heating value of torrefied to raw biomass. The enhancement factor of HHV reflects the energy output and energy densification of the torrefied biomass (Chen *et al*., 2020). It was calculated using equation 7

$$Enhancement\ factor = \frac{HHV\ of\ torrefied\ product\ (\ (MJ/kg)}{HHV\ of\ raw\ biomass\ (\ (MJ/kg)\ )} \qquad (7)$$

RESULTS AND DISCUSSION

The Physical Appearance of Solid Product of Torrefaction

The physical appearance of raw and torrefied biomass under various operating conditions are shown in figure 2. The color of the raw biomass was either light brown or orange. However, the torrefied solid samples have brown, dark brown, and black colors at 200, 250 and 300 °C, representing light, moderate and severe conditions respectively. As torrefaction proceeds, the cell structure of the biomass undergoes significant chemical changes, which is evident by progressive change in colour of the solid products, resembling fine coal. The color of moderately torrefied biomass might result from the synthesis of phenols and aldehydes under moderate torrefaction conditions (250 °C). This conclusion is similar to what was observed during the torrefaction of sesame stalk and bean husk (Khairy *et al*, 2024).

Figure 2: Physical Appearance of Solid Fuel at Different Torrefaction Temperatures

Physicochemical Properties

Properties of Raw Biomass Samples

The major properties of the raw biomass determined are ultimate, proximate, higher heating value (HHV) and fiber analyses presented in Table 1 in comparison with published results for some biomass such as sesame stalk, bean husk and spent coffee grounds (SCG). Raw PKS and RH have relatively low moisture contents between 7.12 % and 7.42 %, which are less than the approved standard of about 10% desirable in the burning process (Abdullah *et al*., 2022) and within the ranges of 4.12% for bean husk (Khairy *et al*., 2024) and 8.70% for corn cob (CC) (Ibitoye *et al*., 2021). The biomass with the higher moisture content was RH (7.42%), which is 1.28% less than that reported for CC and 3.3% higher than that of bean husk. The largest percentage of the proximate analysis is composed of volatile matter, with values of 70.98% in PKS, which is 5.1% higher than 65.88 % in RH. These values are comparable with 64.18% VM reported for bean husk (Khairy *et al*., 2023) and 69.98% for betel nut shell (Phengpom *et al*., 2023) but VM in PKS is 10.2% less than 81.18% reported for corn stover (CS) (Xing *et al*., 2024). These results showed that these biomass are highly reactive, ignitable and suitable for energy application (Abdullah *et al*., 2022). The AC in RH (9.04%) is almost double that of PKS, 4.48%. These values are within the ranges of 3.95% for corn stover and 10.12% for corn cob (Xing *et al*., 2024; 1bitoye *et al*., 2021), but is 12.01% and 13.13% less than 21.05% and 22.17% reported for sesame stalk and bean husk (Khairy *et al*., 2024). The fixed carbon content, 17.42,% obtained for PKS was only 0.24% higher than 17.66% for RH, which are greater than 15.98% and less than 18.07% obtained for sugarcane baggase (SCB) and betel nut shell (Granados *et al*., 2021 and Khairy *et al*., 2024).

The elemental composition of PKS and RH are presented in Table 1. Among these, Carbon and Oxygen have the highest values, followed by Hydrogen, whereas, Nitrogen and Sulphur contents were found to be relatively low. Carbon, hydrogen and oxygen contents of RH are 43.67, 5.72 and 49.85% respectively whereas, the values for PKS are 47.7, 6.93 and 44.7%. These values are within the ranges of values reported for similar studies, such as 49.03, 6.06 and 36.82% for corn stover (Xing *et al*., 2024) and 41.24, 6.10 and 35.82 for corn cob (Ibitoye *et al*., 2021). Raw PKS and RH had HHV equivalent to 18.92 and 15.98 MJ/kg, which is within the range of values reported in the literature for PKS and RH (Ahmad *et al*., 2023, Chen *et al*., 2021). When compared to bean husk (Khairy *et al*., 2024), betel nut shell (Phengpom *et al*., 2023) and sugarcane baggase (Granados *et al*., 2021), PKS and RH show similar characteristics, which suggest that they are potential alternatives to traditional solid biomass fuels, given their comparable higher heating values (HHVs). However, the data indicated that rice husk has a lower HHV, around 15.98 (1.06) MJ/kg than PKS, 18.92 (1.44) MJ/kg potentially due to its higher moisture and oxygen contents. The fibre content of PKS and RH are shown in Table1. The hemicellulose (HC), cellulose (CEL) and lignin (L) content in PKS are 20.4, 38.2 and 23.8 % while those of RH are 24.52, 35.1 and 22.21 respectively.

Table 1: Physicochemical Properties of the Biomass before Torrefaction

Biomass		**RH**	**PKS**	**Corn Cob (CC)**	**Corn Stover (CS)**	**Betel nut shell**	**Sesame stalk (SS)**	**Bean husk(BH)**	**Sugarcane baggase (SCB)**
Ultiimate (%)	C	43.67	47.7	41.24	49.03	NA	44.5	32.77	42.09
	H	5.72	6.93	6.1	6.06	NA	5.28	4.77	5.42
	O	49.85	44.7	35.87	36.82	NA	48.87	61.3	51.5
	N	0.76	0.52	0.12	0.903	NA	0.95	1.1	0.18
	S	0.17	0.15	1.56	NA	NA	0	0.05	NA
Proximate (%)	MC	7.42	7.12	8.7	3.23	7.2	5.13	4.12	NA
	VM	65.8	70.9	71.12	81.18	69.98	63.57	64.18	81.86

Biomass		**RH**	**PKS**	**Corn Cob (CC)**	**Corn Stover (CS)**	**Betel nut shell**	**Sesame stalk (SS)**	**Bean husk(BH)**	**Sugarcane baggase (SCB)**
	AC	9.04	4.48	10.12	3.95	4.81	21.05	22.17	2.03
	FC	17.6	17.4	10.6	11.64	18.07	10.25	9.69	15.98
Lignocellulose (%)	HC	24.52	20.4	NA	NA	NA	17.49	14.94	35.21
	CEL	35.1	38.2	NA	NA	NA	63.96	67.68	37.59
	L	22.21	23.8	NA	NA	NA	18.8	17.38	27.2
HHV		15.98	18.92	14.1	20.59	17.29	18.05	14.98	16.79
Reference		This work		Ibitoye *et al*., 2021	Xing *et al*., 2024	Phengpom et al., 2023	Khairy *et al*., 2024		Granados *et al*., 2021

HC – Hemicellulose, CEL- Cellulose, L- Lignin

Physicochemical Analysis of Torrefied Biomass

Effect of Torrefaction Temperature and Time on Proximate Analysis

The impact of torrefaction temperatures on the biomass feed stocks were examined at three torrefaction temperatures of 200, 250 and 300 ^{0}C at different torrefaction time of 35 and 60 mins.

Figure 3 depicts the effect of the temperature and time on the fixed carbon (FC) content of the torrefied biomass in which the FC contents increased from 21.71 - 31.84% and 22.26 – 33.19% in PKS and RH respectively, with the increasing temperature from 200 – 300 ^{0}C. However, the volatile matter content decreased from 70.98 and 65.88 in raw PKS and RH to 66.22% and 59.65% at 200 ^{0}C, 35 mins and decreased significantly to 55.68% and 46.69% at 300 ^{0}C, 60 mins in PKS and RH respectively. PKS retained the highest proportion of volatiles even after torrefaction at 300 °C than RH, indicating greater stability of the organic matrix in the form of FC. The increase in the fixed carbon content of the torrefied biomass could be as a result of loss of volatile matter, which consist of light hydrocarbons and small molecules with hydrogen and oxygen, together with the possible thermochemical changes in lignocellulose constituents (Khamwichit *et al*., 2024; Premchand *et al*., 2023). An increase in fixed carbon indicates that torrefied solid products have a higher heating value than raw samples. This observation is similar to the results obtained by Torres *et al*., 2023, when the fixed carbon of wheat straw increased from 11.45 t0 31.48%, and Chen *et al*., 2020, when the volatile matter content of RH decreased from 65.32% to 41.26% during non-oxidative torrefaction as the temperature was increased from 220 °C to 300 °C. As the torrefaction proceeded, the drying period was likely to take place at the beginning stage in which the free moisture was likely to diffuse out of the biomass sample. The ash content increased significantly from 4.48% to 9.73% and 9.04 to 16.33 in PKS and RH respectively as torrefaction temperature increased from 200 -300 ^{0}C. This is because higher torrefaction temperature promoted the thermal degradation of biomass as more volatile substances were released (Chen *et al*., 2020). This observation is in agreement with previous findings on RH and PKS (Chen *et al*., 2021). It has been shown that the thermal breakdown of complex polymers at higher torrefaction temperatures results in a rise in FC and the quantity of ash with a reduction in volatile matter (Inovaski *et al*., 2022).

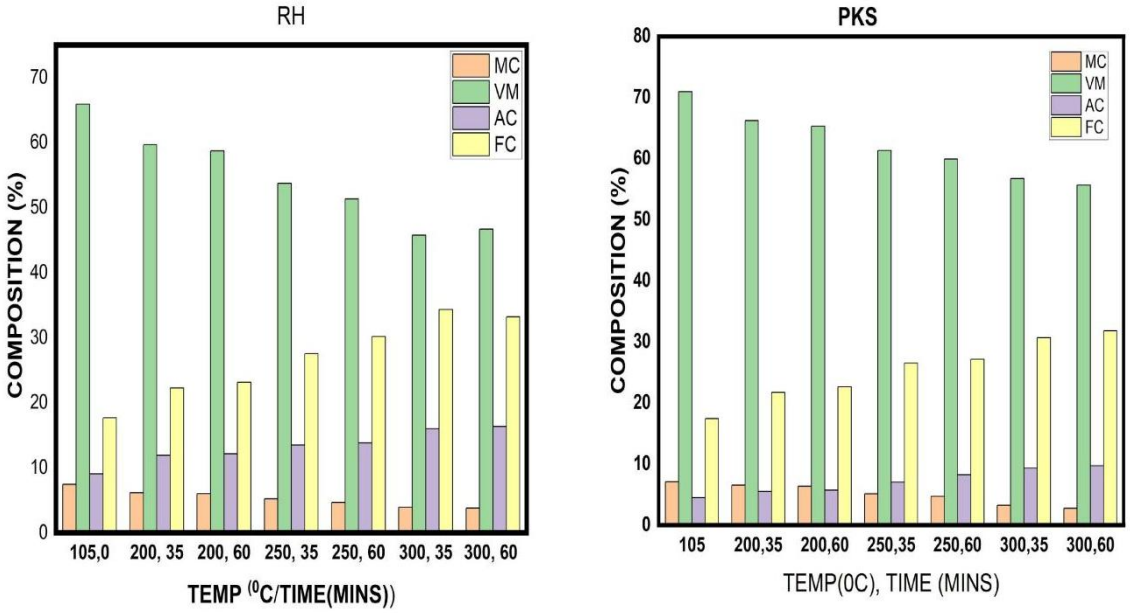


Figure 3: Proximate Composition of Raw (105 ^{0}C) and Torrefied (a) PKS and (b) RH at 200, 250 and 300 ^{0}C for 35 and 60 mins

Elemental Compositions Solid Fuel from PKS and RH

The carbon content gradually increased from 47.7 % and 43.67% in raw PKS and RH with an increase in torrefaction temperature and time to 61.05 % and 56.71 at 300 ^{0}C, 60 mins, whereas the oxygen content reduced from 44.7 % and 49.85% in PKS and RH to 33.23 % and 37.61% as the temperature and increased to 300 ^{0}C. Similarly, at 300 ^{0}C, the carbon content increased from 59.27 % to 61.05 % and 54.39% to

56.71% in PKS and RH respectively, as the residence time increased from 35 to 60 mins. The effect of temperature was more pronounced than residence time on the elemental compositions of both PKS and RH. A similar trend was observed by Ahmad *et al*., 2023, when the carbon content was increased from 45.2 – 52.3% with a decrease in oxygen content from 49.5 – 42.2% as the temperature increased from 200 – 300 ^{0}C. This was mainly as a result of dehydroxylation and decarboxylation reactions which occurred during the hemicellulose degradation process. The higher oxygen content in RH than PKS leads to lower HHV in RH than PKS (Cui *et al*., 2024.). The transformation of elements was as a result of the liberation of water and volatiles due to the degradation of fiber during torrefaction process. These processes also contributed to a reduction in O content (Kumar *et al*., 2021). This higher carbon content and lower oxygen content in torrefied biomass contributed to enhanced fuel performance of the biomass material (Cui *et al*., 2024).

Hydrogen–Carbon (H/C) and Oxygen-Carbon (O/C) Ratio of Torrefied PKS and RH

A comparison of the O/C and H/C ratios for coals and torrefied PKS and RH are also presented in Table 2. O/C and H/C atomic ratios are very important in accessing the fuel quality in torrefied biomass as the preferred O/C ratios for the torrefied biomass for solid fuel applications should be in the range of 0.1–0.7, with comparable values of 0.38 to 0.91 for fossil coal (Niu *et al*., 2019). The atomic O/C ratios decreased remarkably after torrefaction from 0.77 to 0.54 and 1.14 to 0.66 while the H/C ratio decreased from 1.14 to 0.82 and 1.06 to 0.84 in both PKS and RH as the temperature increased from 200 – 300 ^{0}C. The decrease in the O/C and H/C ratios were mainly due to the release of water and light volatile substances via dehydration, deoxygenation, and dehydrogenation during torrefaction (Pinsamarn *et al*., 2024). These values are similar to those reported in previous studies (Chen *et al*., 2020; Torres *et al*., 2023; Mueanmas and Rakmak, 2023). Torrefied PKS and RH are very desirable due to their compositional similarities to lignites that have 0.395 for O/C and 0.98 for H/C and peats have 0.428 for O/C and 1.266 for H/C (Ibarra *et al*., 1997).

Table 2: Elemental Composition of Raw and Torrefied Biomass at 200, 250 and 300 ^{0}C

Biomass		C	H	O	N	S	O/C	H/C	Reference
RH	Raw	43.67	5.72	49.85	0.76	0.17	1.14	1.13	This work
	200	49.3	5.21	44.68	0.81	0.12	0.91	1.06	
	250	52.24	5.02	41.86	0.88	0.11	0.80	0.96	
	300	56.71	4.77	37.61	0.91	0.08	0.66	0.84	
PKS	Raw	47.7	6.93	44.7	0.52	0.15	0.94	1.45	
	200	52.8	6.02	40.5	0.56	0.12	0.77	1.14	
	250	57.1	5.29	36.92	0.58	0.12	0.65	0.93	
	300	61.05	5.01	33.23	0.61	0.1	0.54	0.82	
Lignite	NA	NA	NA	NA	NA	NA	0.4	0.98	Ibarra *et al*., 1997
Peat	NA	NA	NA	NA	NA	NA	0.43	1.27	
Reference Coal							0.320	0.86	Barrera *et al*., 2014

Higher Heating Value (HHV) and Enhancement Factor (EF) of Torrefied Solid Products

The Higher heating value (HHV) and EF of solid products of each of the biomass at different operating conditions are presented in Table 3. The HHV of torrefied PKS and RH increased with rising temperature and holding time. Raw PKS and RH had HHV of 18.92 (1.44) and 15.98 (1.07) MJ/kg, which later increased to 22.89 (3.35) MJ/kg and 18.93 (0.34) MJ/kg respectively as temperature and residence time increased from 200 to 300 ^{0}C and 35 to 60 mins, corresponding to the sub-bituminous type B and C coal range. The results obtained are consistent with literature findings on PKS and RH (Ahmad *et al*., 2023; Chen *et al*., 2021), confirming the suitability of torrefied PKS and RH for thermochemical conversion. This conforms to the results obtained as the HHV of torrefied wheat straw increased from 13.86 to 19.41 MJ/kg with rising temperature and holding time from 230 to 305 °C and 40 to 60 mins (Torres *et al*., 2023). The increase in the heating value is significantly noticeable in the temperature range of 200-250°C, while in the range of 250-300 °C, only a slight difference is observed for both PKS and RH as shown in Table 3. Also, the effect of time was more pronounced at 250 ^{0}C than at 300 ^{0}C. This observation is similar to the results obtained by Chen *et al*., 2023; Phengpom *et al*., 2023. The increase in HHV of biomass during torrefaction was as a result of the removal of a higher amount of oxygen compared with carbon (Ho *et al*., 2018). It also contributed to the dehydration and depolymerization of hemicellulose, which resulted in an increase in the content of fixed carbon, elemental carbon, and lignin, which finally led to a rise in the energy content of the biomass ((Zhang *et al*., 2022; Torres *et al*., 2023).

Torrefaction's efficacy has always been measured using the enhancement factor (EF) since it represents the change in HHV that occurs during torrefaction process. The EF values determined for this study are shown in Table 3. The EF values increased in both PKS and RH with temperature and residence time, indicating that HHV levels enhanced throughout the process. The EF of torrefied PKS and RH increased from 1.05 at 200 ^{0}C, 35 mins to 1.21 at 300 ^{0}C, 60 mins and 1.06 at 200 ^{0}C, 35 mins to 1.18 at 300, 60 mins respectively. The optimum values being obtained at temperature 300 °C and residence time 60 mins. The enhancement in energy density for torrefied biomass was attributed to the release of volatile substances and dehydration reactions, resulting in a rise in fixed carbon content but decline in O/C ratio. Additionally, the lesser reduction in energy yield contributed to the increase in energy density. This conclusion is reasonable since carbon densification leads to an increase in products energy generated at a higher temperature. PKS enhancement factor is higher than 1.163 and 1.13 obtained for sesame stalk and bean husk (Khiary *et al*., 2024).

Tables 3: Higher Heating Value and Enhancement Factor of Torrefied PKS and RH

Biomass	PKS				RH			
	HHV		EF		HHV		EF	
Time	35	60	35	60	35	60	35	60
Temperature								
200	19.89	20.12	1.05	1.06	16.93	17.25	1.06	1.08
250	20.92	21.5	1.11	1.14	17.89	18.40	1.12	1.15
300	22.51	22.89	1.19	1.21	18.72	18.93	1.17	1.18

Structural Analysis

The structural analyses carried out include fibbre, FTIR and SEM analyses

Fibre Analysis

The fibre contents, hemicellulose (HC), cellulose (C) and lignin (L) of PKS and RH are shown in Figure 4. During light torrefaction at 200°C, 35 mins, a small amount of hemicellulose were removed, while lignin and cellulose were affected to a lesser extent. As temperature increased from 200 to 300 °C, hemicellulose content drastically declined from 20.4 to 8.33% and 24.52 to 10.43% and cellulose content decreased from 38.2% to 26.78% and 35.1 to 23 % in PKS and RH respectively. Conversely, temperature has a limited effect on lignin content as it increased from 23.8 to 48.44 % and 22.2 to 48.4 % in PKS and RH because of the wide thermal degradation temperature range of lignin (Sun *et al*., 2023). The higher lignin content for PKS was responsible for its higher resistance to thermal degradation than rice husk as the torrefaction temperatures increased. When the biomass were torrefied at the same temperature with increased residence time (from 35 to 60 mins, further reduction in the hemicellulose and cellulose contents were observed as shown in Figure 5. This was in accordance with the previous research that hemicelluloses were the most reactive compounds among carbohydrates in biomass (Li *et al*., 2018; Akinrinola *et al*., 2020; Khiary *et al*., 2024).

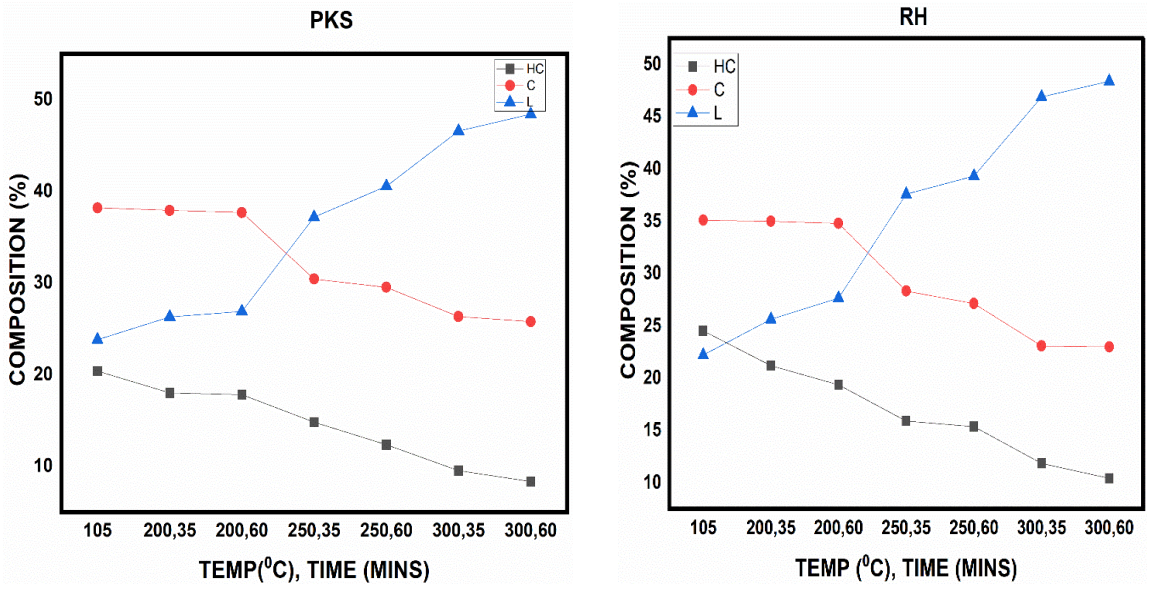


Figure 4: Fibre Composition of Raw (105 ^{0}C) and Torrefied PKS and RH

Functional Group Determination and Surface Morphology of Solid Fuel

The FTIR spectra for raw and torrefied PKS and RH at 200,250 and 300 ^{0}C are shown in Figure 5. A broad absorption band around 3400 cm^{-1} which is characteristic of cellulose, hemicellulose and the presence of moisture was clearly present in the raw samples and those treated at 200 °C in both PKS and RH, corresponding to the stretching of the O–H bonds of the hydroxyl groups, As torrefaction temperature is increased from 250 °C to 300 °C, this band gradually disappeared, indicating that the hydroxyl-rich components are dehydrated and decomposed. At lower temperatures of 250, the peaks at ~2915 in PKS and ~2925 cm^{-1} in RH were also pronounced, which can be attributed to the stretching of C–H bonds in aliphatic chains (Ubanci *et al*., 2025). It is observed that all the peaks have similar characteristic in both PKS and RH, in that the peak intensities decreased with increase in torrefaction temperatures from 200 – 300 ^{0}C. This showed that torrefaction process has progressively eliminated functional groups such as -OH and C=O through deoxygenation reactions such as dehydration, decarbonylation and decarboxylation (Urbancl *et al*., 2025).

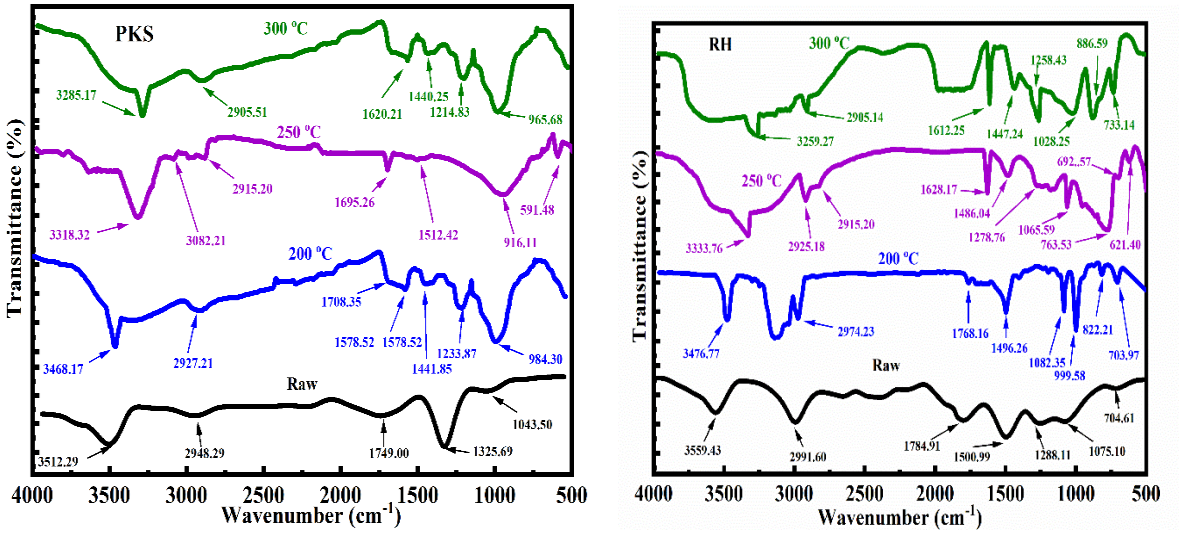


Figure 5: FTIR Spectra for Raw and Torrefied PKS and RH at 200, 250 and 300 ^{0}C

The impact of torrefaction on the surface morphology of PKS and RH was investigated using SEM–EDX analysis as shown in figure 6. The raw PKS and RH displayed smooth, compact surface and intact fibrous structure with minimal surface deformation, which indicates that the lignocellulosic of the biomass (cellulose, hemicellulose, and lignin) remain structurally unaltered (Hari *et al*., 2025). Compared to the raw biomass, increased structural deformation and clear transformation in surface morphology is detected in torrefied biomass with the increase in torrefaction temperature from 200 to 300 ^{0}C. The torrefied PKS and RH displayed a rougher, more porous texture with numerous micro-cracks and partially collapsed cell walls as the damage to the sample structure was more significant (Chen *et al*., 2021). At the highest torrefaction condition of 300 ^{0}C, extensive structural alteration occurred in torrefied PKS and RH, characterized by a sharp increase in the presence of irregular fractured particles. This significant deformation is consistent with advanced thermal degradation due to the depletion of hemicellulose and a small part of cellulose (Ivanovski *et al*., 2022, Hari *et al*., 2025). These findings are in line with previous studies reporting similar transitions in thermally pretreated lignocellulosic materials (Sukiran *et al*., 2020; Chen *et al*., 2021).

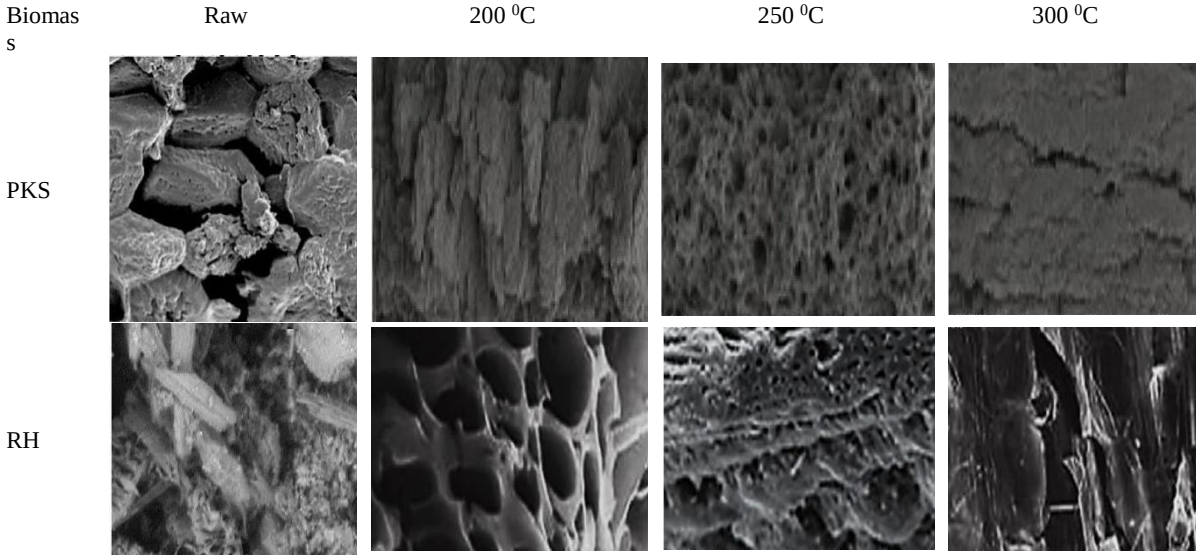


Figure 6: SEM Images of Raw and Torrefied PKS and RH

Mass and Energy Yield of Solid Fuel

The results of the mass and energy yields of PKS and RH (MY and EY) at various temperatures and times are shown in Figure 7. The mass and energy yield of both PKS and RH gradually decreased following a declining pattern with increasing torrefaction severity (i.e., temperature and residence time) from 200 ^{0}C to 300 ^{0}C and 35 mins to 60 mins. In PKS, mass and energy yield reduced from 81.75 (9.60) % to 56.56 (6.51) % and 85.84 (6.65) % to 68.44 (3.66) %, while those of RH decreased from 82.55 (11.29) % to 53.28 (3.75) % and 87.50 (9.40) % to 62.87 (2.62) %. Torrefaction temperature has a remarkable effect on the mass yield and energy yield of torrefied PKS and RH. At 200 ^{0}C, increasing the residence time from 35 mins to 60 mins had a significant effect on mass and energy yield as it reduced from 81.75 (9.60) % to 72.15 (6.21) % and 85.84 (6.65) % to 76.48 (3.23) % in PKS, and from 82.55 (11.29) % to 72.15 7.77) % and 87.50 (9.41) % to 77.92 (6.28) % in RH. However, increasing the residence time from 35 min to 60 min had a slight effect on mass and energy yield at 250 ^{0}C and 300 ^{0}C temperatures. Hemicellulose is the least thermally stable materials, which can release small molecular gases at relatively low

temperature. RH has lower mass yield than PKS due to its higher content of hemicellulose, which can release small molecular gases at relatively low temperatures. These observations seem to agree with those earlier reported for PKS, RH, sesame stalk and bean husk (Ahmad *et al*., 2023; Chen *et al*., 2020; Khiary *et al*., 2024).

The decrease in solid mass yield with increasing temperature and time is attributed to the decomposition of hemicellulose and cellulose components, and reduction in volatile matter in torrefied products lead to reduced mass and energy yields in PKS and RH (Sukiran *et al*., 2020; Pinsamarn *et al*., 2024). These results were in agreement with the results obtained from of betel nut shell treated by torrefaction from 200 to 300 ^{0}C under a nitrogen atmosphere, which resulted in a decrease in energy yield from 99.29 to 48.72% (Phengpom *et al*., 2023). Similarly, PKS subjected to torrefaction in nitrogen under identical conditions exhibit a decrease in mass and energy yield from 82.9 % to 44.8 %and 70.8 % to 40.5 %, reflecting a reduction of 23.86 %. as the temperature increased from 200 ^{0}C, 30 mins to 300 ^{0}C, 60 mins (Ahmad *et al*., 2023).

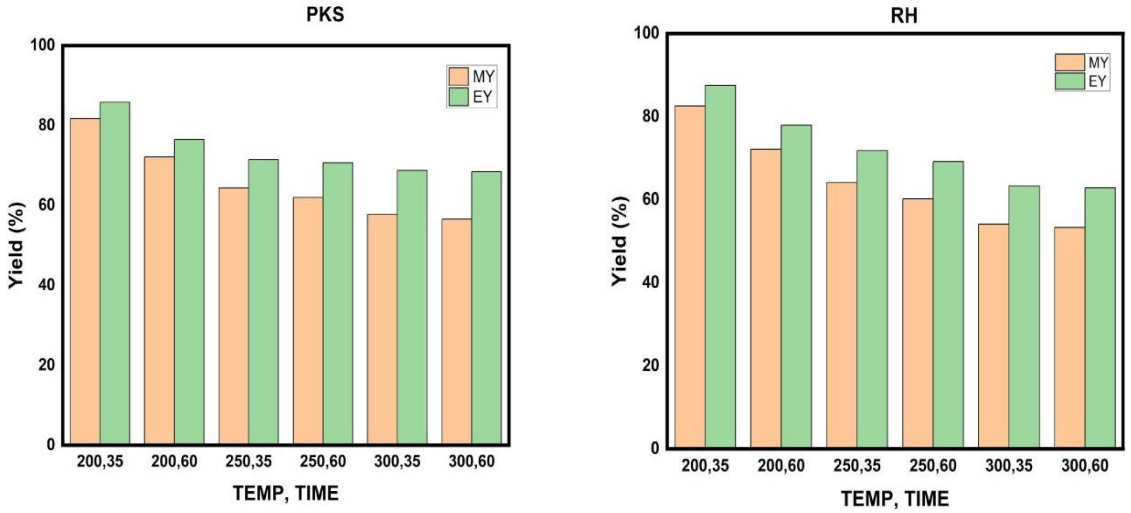


Figure 7: Effect of Temperature and Time on Mass and Energy Yield of Torrefied PKS and RH

CONCLUSION

This study typically considered agricultural biomass such as rice husk and oil palm kernel shells as competitive alternatives to traditional biomass resources in the biofuel industry. The decrease in the O/C and H/C ratios in torrefied PKS and RH made the biomass comparable to lignite and peat in terms of fuel quality. The maximum HHV of biochars from PKS and RH increased to 22.89 MJ/kg and 18.93 MJ/kg at the expense of decrease in MY and EY especially at the severe torrefaction condition, that is, 300°C, 60 mins. The results have shown the correlation and the differences in the torrefaction behavior of PKS and RH under the same condition and emphasize the higher potential of using PKS than RH for the production of biofuel through torrefaction for further use in other thermochemical conversion processes for sustainable energy practices. Torrefaction of these agricultural biomass did not only make the biomass suitable for bioenergy applications but also contributes to reducing environmental impacts by converting agricultural biomass into renewable energy, thereby bringing worth out of wastes.

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