Agro-Industrial Waste Upgrading via Torrefaction Process – A Case Study on Sugarcane Bagasse and Palm Kernel Shell in Thailand

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ABSTRACT

In this research, the upgrading of agro-industrial wastes was investigated by using the torrefaction pretreatment technique. Two types of biomass waste, including sugarcane bagasse (SBG) and palm kernel shell (PKS), were used as raw materials. The operating conditions, i.e., torrefaction temperature and residence time, are between 225–300 °C and 30–90 minutes. The findings show that, in terms of mass yield and calorific value of the solid product, the torrefaction temperature is a more sensitive parameter than the residence time. By increasing the torrefaction temperature from 225 to 300 °C, the mass yields are dropped in the range of 28.79–31.57 wt.% and 28.00–29.88 wt.%, while the effect of holding time exhibits the mass yield decreasing only 3.12–5.90 wt.% and 1.53–3.41 wt.%, for SBG and PKS torrefaction, respectively. In terms of calorific value, higher heating values increase as torrefaction severity increases, varying in the range of 0.29–2.84 MJ/kg, with torrefaction temperature as the dominant factor. Regarding the calorific value, energy yield, energy gain, and energy-mass co-benefit index, the optimal operating conditions for SBG and PKS torrefactions are the same condition as 275 °C for 90 minutes. SBG and PKS bio-coals obtained from torrefaction are promising solid fuels with high calorific value (about 23 MJ/kg), with an energy yield of 73.93–77.41%, relative to coal that could be further utilized for co-firing in thermal power plants.

Keywords: torrefaction, sugarcane bagasse, palm kernel shell, optimal condition.

INTRODUCTION

Agro-industrial waste is one of the renewable resources suitable for biofuel production by using biochemical and thermochemical conversion processes, e.g., fermentation, saccharification, anaerobic digestion, carbonization, pyrolysis, and gasification. Compared to biochemical technology, the thermochemical conversion process is a remarkable and the most important pathway for biofuel production. The thermochemical process has numerous advantages, including a small footprint, efficient nutrient recovery, a short reaction time, as well as the ability to handle a wide range of wastes and blends [Chen et al., 2021]. Among thermochemical technology, torrefaction is an intriguing pretreatment process for converting biomass into energy-dense solid fuel, called torrefied biomass, which is a potential candidate as an alternative fuel to coal. In theory, the term "torrefaction" refers to the thermal treatment of biomass in an inert atmosphere at 200–300 °C and atmospheric pressure. With the elimination of moisture and certain volatile components containing most of the oxygen in the biomass structure, the calorific value of the remaining material is enhanced. Torrefied biomass demonstrates a number of benefits, including low moisture content, high energy density, good hydrophobicity, enhanced grindability, lower storage and transportation costs, and others [Niu et al., 2019]. Furthermore, compared to coal, the burning of torrefied biomass reportedly releases less harmful metals, nitrogen oxides (NO_x), sulfur oxides (So_x), and greenhouse gases like carbon dioxide (CO_2) [Ren et al., 2017; Rokni et al., 2018; Yanik et al., 2018].

Specifically, Thailand is one of the top five countries exporting sugar and palm oil, and

consequently, the volumes of agro-industrial waste, i.e., sugarcane bagasse (SBG) and palm kernel shell (PKS) produced are enormous. In practice, most SBG and PKS have been used directly without any pretreatment as solid fuels for heat and process steam production. Torrefaction, however, could be taken into account for SBG and PKS upgrading because of the heterogeneous characteristics, low calorific value, and high moisture content of such-as-received agro-industrial wastes. To date, many researchers studied torrefaction of agricultural and agro-industrial waste continually in a variety of areas. Although various notable studies have been reported on lignocellulosic biomass waste torrefactions, the variances in the qualities and characteristics of torrefied biomass products are primarily influenced by the plant species, the characteristics of raw biomass residues, which vary with geographic location, and the operational parameters employed for torrefaction. For instance, the higher heating value of raw SBG in Pakistan is reported as 16.53 MJ/kg [Kanwal et al., 2019] while 18.31 MJ/kg for SBG in Taiwan [Du et al., 2014], implied that the optimal condition for SBG torrefaction pretreatment of each SBG sample would be different.

Considering the importance of biomass waste utilization, this research aimed to examine the upgrading of the two abundant Thai agro-industrial wastes, i.e., SBG and PKS, via the torrefaction process. The most appropriate operating conditions, including the torrefaction temperature and residence time, which achieved the highest energy efficiency, would be suggested. The experimental findings mentioned in this paper would be helpful information for the torrefaction process of SBG and PKS could be employed as a solid fuel for industrial and thermal applications.

MATERIALS AND METHOD

Sample preparation and characterization

The SBG and PKS samples used in this investigation were obtained from the local industries nearby Rayong province, Thailand. The biomass samples were first thoroughly cleaned with water, then divided into small pieces and dried in the sun for 3 to 5 days. Finally, the samples were ground in a grinding device that can be sieved to an average size of 0.5 and 1 mm for further characterization and torrefaction experiments, respectively.

The raw materials and torrefied samples were subjected to proximate analysis, which included measuring the moisture (MC), volatile matter (VM), fixed carbon (FC), and ash (A) contents using a thermogravimetric approach (TA instrument Q50 analyzer) that was adopted from the literature [Mayoral et al., 2001]. In brief, the thermogravimetric proximate experiment constitutes three different steps: (i) The drying step in an inert atmosphere in which the moisture content is considered as the losing weight when the material is heated at 50 °C/min till 110 °C and the temperature is maintained for 10 minutes. (ii) The devolatilization step in an inert atmosphere in which the sample is subsequently heated to 800 °C at a rate of 50 °C/min and maintained isothermally at this temperature for 8 minutes. The volatile matter content is responsible for the weight loss at this interval. (iii) The combustion step started with the automatic switch of inert gas into the air and the temperature is kept constant for 5 minutes to allow complete combustion. The fixed carbon content of the sample is responsible for the mass loss from combustion. Lastly, the residual weight remaining corresponds to the ash content. For proximate analysis of the biomass and torrefied samples used in this investigation, a typical TG profile is depicted in Figure 1. To determine the calorific value, the oxygen bomb calorimeter (Parr 1341) data was used to calculate the higher heating value (HHV). To ensure accuracy and reliability, proximate analysis and calorific value assessments of raw materials and torrefied biomass were carried out at least twice. In addition, A Perkin-Elmer FTIR spectrometer was used to examine the chemical structural features found in the raw and torrefied biomass samples.

Torrefaction procedure

The schematic diagram for the torrefaction experiment, which was conducted in a quart tube fixed bed reactor with a 26 mm ID and 600 mm length, is shown in Figure 2. Briefly, a quartz tube with quartz wool plugs on each of its ends was used to hold the 5 g, 1 mm biomass sample in the center. A 100 ml/min flow rate of nitrogen was utilized as the carrier gas. The volatile product was condensed by a series of the condenser to
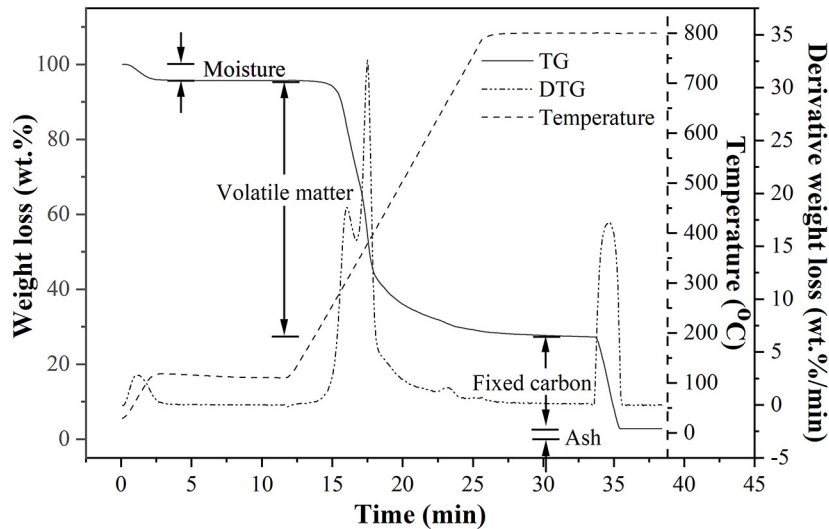
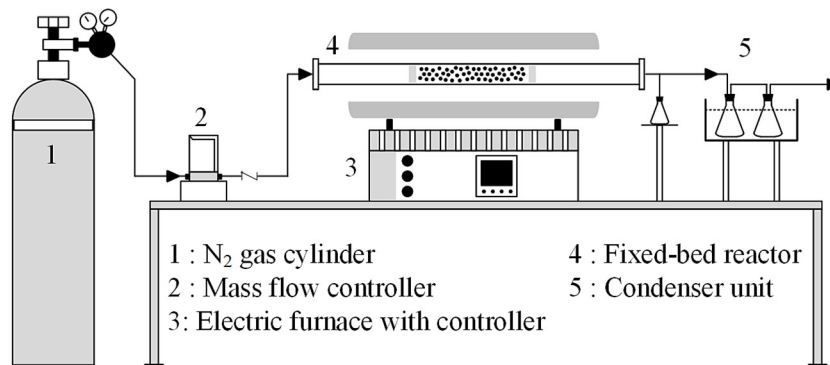**Figure 1.** Thermogravimetric proximate analysis for biomass sample

Figure 2. Schematic diagram of torrefaction experiment

collect the amount of liquid product. SBGXY and PKSXY, which stand for SBG and PKS samples, respectively, and designate different operating conditions, were created. X stands for the torrefaction temperature (225, 250, 275, and 300 °C), while Y stands for the residence duration (30, 60, and 90 min). For experimental results with a 95% confidence level, each operating condition was replicated three times.

The following formulas were used to determine the yields of the torrefied products, including the yields of liquid, non-condensable gas, and solids (also known as mass yields, or MY):

$$Solid\ yield = \frac{mass\ of\ torrefied\ biomass}{mass\ of\ raw\ biomass} \times 100\% \quad (1)$$

$$Liquid\ yield = \frac{mass\ of\ liquid\ product}{mass\ of\ raw\ biomass} \times 100\% \quad (2)$$

$$Gas\ yield = 100\% - solid\ yield - liquid\ yield \quad (3)$$

Enhancement factor (EF), energy yield (EY), and energy gain (EG) were among the parameters that were determined using the following expressions:

$$Enhancement\ factor\ (EF) = \frac{HHV\ of\ torrefied\ biomass}{HHV\ of\ raw\ biomass} \quad (4)$$

$$Energy\ yield\ (EY) = MY \times EF \quad (5)$$

$$Energy\ gain\ (EG) = \frac{\left(\dfrac{HHV\ of\ torrefied\ biomass - HHV\ of\ raw\ biomass}{HHV\ of\ raw\ biomass}\right)}{\left(\dfrac{mass\ of\ raw\ biomass - mass\ of\ torrefied\ biomass}{mass\ of\ raw\ biomass}\right)} \times 100\% \quad (6)$$

RESULTS AND DISCUSSION

Physical properties of biomass

Table 1 displays the basic characteristic data of the biomass samples. After sun-dried conditions or air-dried basis, the biomass samples reveal the moisture contents are in the range of 7.46–7.62 wt.%. Both SBG and PKS are dominated by volatile matter (87.95 and 75.25 wt.%). It should be noted that SBG shows lower contents in fixed carbon compared to PKS, further altered to calorific value. On the other hand, PKS exhibits higher ash content than SBG, because PKS contained many oxides such as SiO_2, CaO, MgO, K_2O, Al_2O_3, and Fe_2O_3 [Ikubanni et al., 2020]. Nevertheless, it can be noticed that the ash content of PKS in this study (3.61 wt.%) is considerably lower than that reported elsewhere (4.38–8.86 wt.%) [Ikubanni et al., 2020; Inayat et al., 2020], suggesting that this PKS is better suited to use as a solid fuel for thermal utilization, because of its high values for fixed carbon and low values for ash contents. According to the information from an oxygen bomb calorimeter, SBG and PKS have higher heating values of 15.83 and 18.15 MJ/kg, respectively, which are about within the typical range of HHV for lignocellulosic biomass (i.e., 16.24–20.30 MJ/kg) [Dai et al., 2019].

Product distribution from biomass torrefaction

The experimental data obtained from SBG and PKS torrefaction processes can be shown in Table 2 and the product distribution results, including non-condensable gas yield, liquid yield, and solid yield, are shown in Figures 3 and 4. It is evident that the non-condensable gas product and the liquid product tend to increase along with the torrefaction severity, i.e., at higher temperatures and longer holding periods, while the solid product, which is the main torrefaction process output, tends to decline. For SBG torrefaction, the non-condensable gas yield, liquid yield, and solid

yield are in the range of 2.76–8.51, 19.66–51.52, and 42.49–77.58 wt.%, respectively. By performing torrefaction on PKS, it yields the gas product, liquid product, and solid product in the ranges of 1.55–12.34, 14.29–34.91, and 52.75–84.16 wt.%, respectively. Nevertheless, it should be noticed that the yield of gaseous product of SBG torrefaction at the temperature of 250 °C is higher than that of 275 and 300 °C, while this phenomenon is not observed in the case of PKS torrefaction, i.e., the amount of gaseous and liquid products increases along with torrefaction severity. This might be explained by the difference in the lignocellulosic composition (hemicellulose, cellulose, and lignin) of SBG and PKS. Theoretically, hemicellulose is easily thermally degraded owing to its amorphous structure and low degree of branched-chain polymerization; compared to hemicellulose, cellulose has a higher degree of polymerization and is a long-chain crystalline polymer that has higher heat stability; and lignin is a complex, highly cross-linked, three-dimensional aromatic polymer, resulting in the highest thermal stability [Basu, 2013]. According to Yang et al. (2007), lignin decomposes throughout a wide temperature range, from ambient to 900 °C, while hemicellulose and cellulose mostly do so between 220 and 315 °C as well as 315 and 400 °C, respectively [Yang et al., 2007]. Therefore, SBG contained hemicellulose (26.30–29.92 wt.%) and cellulose (28.25–45.45 wt.%) as the main constituent [Chen et al., 2012; Granados et al., 2017; Kanwal et al., 2019], and high volatile matter content (87.95 wt.%) releases the volatile compounds abundantly, resulting in a high amount of liquid product suppressed the non-condensable gas portion at the torrefaction temperature of 275 and 300 °C. It was reported that as a result of secondary reactions and the breakdown of condensable volatiles into organic compounds with low molecular molecules, the product yields from the torrefaction of wheat-barley straw undergo non-linear variations [Jagodzińska et al., 2019]. In comparison to SBG, PKS has less hemicellulose and cellulose and has a higher lignin concentration (46.21–50.70 wt%) [Sabil et al., 2013; Sukiran et al., 2017; Xu et al.,

Table 1. Characteristics of sugarcane bagasse and palm kernel shell

Sample	Proximate analysis (wt.%)				Calorific value (MJ/kg)
	MC	VM	FC	A	
Sugarcane bagasse	7.46	87.95	3.10	1.49	15.83
Palm kernel shell	7.62	75.25	13.52	3.61	18.15

2021], some volatile compounds released during the torrefaction can be cracked into small gaseous molecules. In addition, because PKS has a high lignin concentration, it should be underlined that the solid product of PKS torrefaction is higher than that of SBG torrefaction. Although this work has not identified the non-condensable gas and liquid product compositions obtained from biomass torrefaction, it could be generally accepted that carbon monoxide, carbon dioxide, and trace amounts of methane make up the majority of the gaseous component of such a product [Manouchehrinejad and Mani, 2018; Niu et al., 2019], whereas water, acids, phenols, ketones, furans, esters, and aldehydes comprise the majority of the liquid component [Chen, 2015; Jagodzińska et al., 2019].

Ordinarily, the two most crucial parameters are mass yield and caloric content of the produced solid product, which can provide the energy yield for evaluating the techno-economic benefits of biomass pretreatment via the torrefaction process. Figures 5–8 present the effect of the operating conditions, i.e., torrefaction temperature (225, 250, 275, and 300 °C) and residence time (30, 60, and 90 minutes), on mass yield and the higher heating
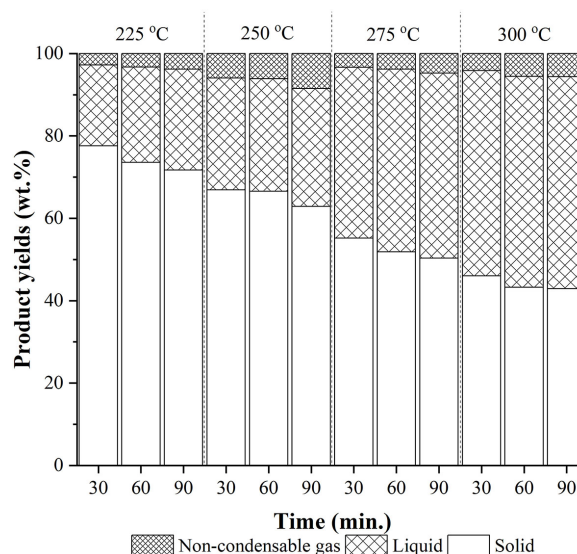
Figure 3. Product distribution of sugarcane bagasse torrefaction

Table 2. Products obtained from sugarcane bagasse and palm kernel shell torrefaction

Sample code	Gas yield (wt.%)	Liquid yield (wt.%)	Solid yield (wt.%)	Higher heating value (MJ/kg)
Sugarcane bagasse torrefaction				
SBG22530	2.76	19.66	77.58	18.29
SBG22560	3.30	23.14	73.56	18.57
SBG22590	3.82	24.50	71.68	19.05
SBG25030	5.93	27.17	66.90	18.99
SBG25060	6.14	27.33	66.53	19.37
SBG25090	8.51	28.63	62.86	19.95
SBG27530	3.37	41.46	55.17	20.64
SBG27560	3.78	44.37	51.85	21.54
SBG27590	4.79	44.87	50.34	23.25
SBG30030	4.13	49.86	46.01	21.46
SBG30060	5.55	51.18	43.27	22.10
SBG30090	5.59	51.52	42.89	24.30
Palm kernel shell torrefaction				
PKS22530	1.55	14.29	84.16	19.88
PKS22560	2.04	15.65	82.31	20.63
PKS22590	2.43	16.82	80.75	20.84
PKS25030	4.29	21.07	74.64	20.83
PKS25060	5.96	21.47	72.57	21.09
PKS25090	5.96	21.76	72.28	21.33
PKS27530	8.48	28.39	63.13	21.66
PKS27560	8.60	29.88	61.52	22.43
PKS27590	8.79	30.71	60.50	23.22
PKS30030	11.95	33.77	54.28	23.36
PKS30060	12.16	34.00	53.84	23.40
PKS30090	12.34	34.91	52.75	23.65

Figure 4. Product distribution of palm kernel shell torrefaction
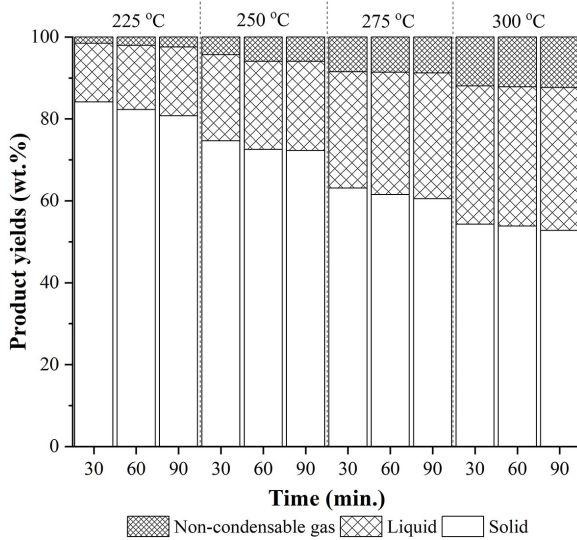

Figure 6. Effect of torrefaction temperature and residence time on palm kernel shell torrefaction mass yield

value of torrefied agro-industrial wastes. Overall, the mass yield of the torrefied biomass product decreases while its calorific value increases as the torrefaction temperature is raised and the holding period is prolonged. With increasing temperature and residence time, mass yields decreased steadily, ranging from 77.58 wt.% to 42.89 wt.% for SBG torrefaction and from 84.16 wt.% to 52.75 wt.% for PKS torrefaction. Nonetheless, it can be clearly observed that (Figures 5 and 6) the torrefaction temperature significantly impacts the mass yield over a given holding period. The mass yield decreases between 28.00 and 31.57 wt.% at a specified holding time when the temperature is raised from 225 °C to 300 °C, although the influence of holding time at a specific torrefaction temperature only affects the
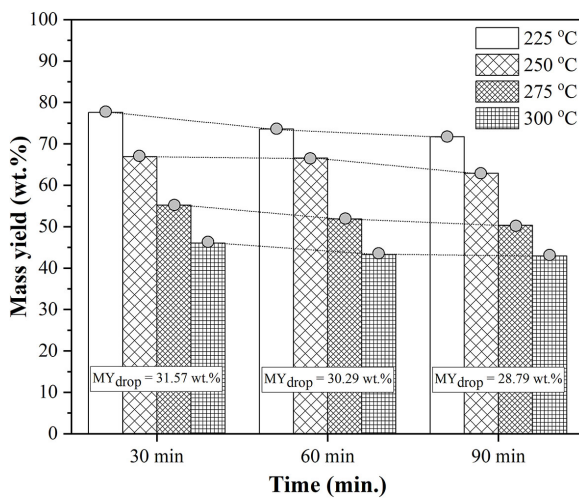
mass yield dropping by 1.53–5.90 wt.%. Furthermore, torrefaction temperature is also the dominant factor at the calorific value point, in which higher heating values improve with increasing torrefaction severity, ranging from 0.29 MJ/kg to 2.84 MJ/kg (Figures 7 and 8). In a study examining the impact of residence time and temperature on the torrefaction of spruce wood, Strandberg et al. (2015) discovered that temperature had a 1.3 to 1.9 times greater impact than residence time and was therefore the most important factor [Strandberg et al., 2015]. Regarding the heating value requirement stated in the solid biofuel specification, i.e., ISO/TS 17225-8 with the value of 21 MJ/kg, it should be noted that optimal torrefaction temperatures of 275 °C seem suitable for SBG, whereas only 250 °C show adequate for PKS pretreatments.

Figure 5. Effect of torrefaction temperature and residence time on sugarcane bagasse torrefaction mass yield

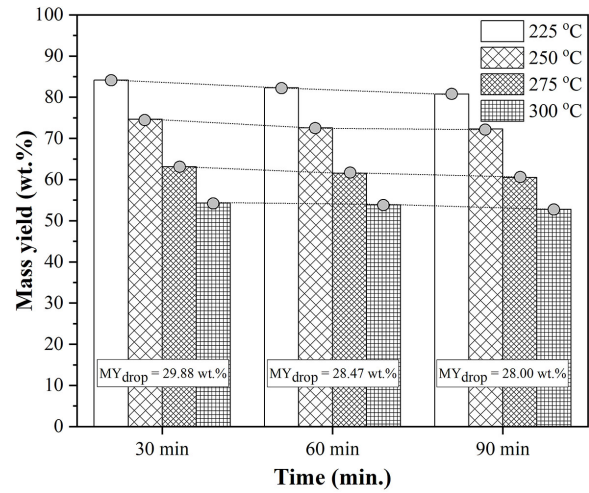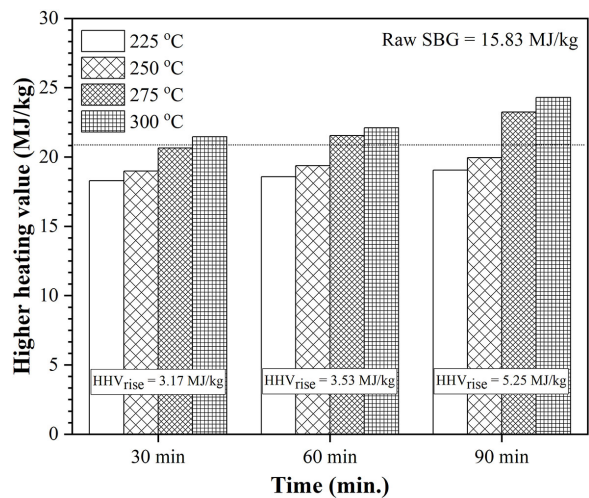**Figure 7.** Effect of torrefaction temperature and residence time on sugarcane bagasse torrefaction calorific value
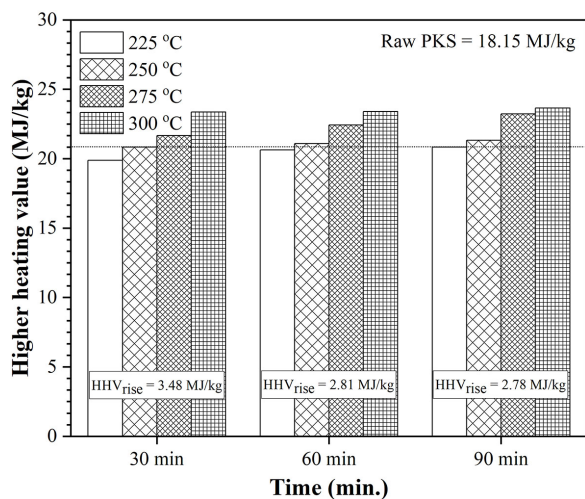
Figure 8. Effect of torrefaction temperature and residence time on palm kernel shell torrefaction calorific value

Additional torrefied solid product characteristics

The torrefied solid products, the main product considered in the torrefaction process, are further focused on fuel characterization. Figures 9 and 10 display the findings of the proximate analysis of the raw and torrefied biomass, respectively. It can be inferred that after torrefaction pretreatment, the moisture contents of torrefied SBG and torrefied PKS, which are in the range of 2.43–4.24 wt.%, do not manifestly any change. Overall, the volatile matter, fixed carbon, and ash levels are significantly impacted by an increase in torrefaction severity. Similar occurrences have been reported for forestry biomass residue (Dyjakon and Noszczyk, 2020), empty fruit bunches (Faizal et al., 2016; Sukiran et al., 2020), food processing waste (Dyjakon et al., 2019), and rice husk (Aslam et al., 2019). The volatile matter of torrefied products decreases as the torrefaction temperature and holding time increase, whereas the fixed carbon and ash contents tend to be higher. Furthermore, the influence of torrefaction temperature on the volatile matter, fixed carbon, and ash contents is larger than that of residence time. In the case of SBG torrefaction, however, the influence of holding time on volatile matter and fixed carbon values is evident when the pretreating temperature is 300 °C, implying that the longer time offers the devolatilization and carbonization of holocellulose processes under these conditions. For PKS, the reduction in volatile matter content and elevation in fixed carbon and ash levels appear to correspond linearly with torrefaction severity,

with an R^2 of 0.95–0.96. Another measure used to estimate the combustibility of solid fuels, particularly coal combustion, is the fuel ratio (FR), which is the ratio of FC to VM [Manatura, 2020]. The FR values of torrefied SBG (0.04–0.14) and torrefied PKS (0.28–0.67) in this investigation appear to increase exponentially with torrefaction temperature and residence time.

The FTIR technique has been used to study different kinds of raw and torrefied biomass, as well as lignocellulosic municipal solid waste, because the presence of hemicellulose, cellulose, and lignin may be recognized by the identification of their functional groups [Ma et al., 2019; Li
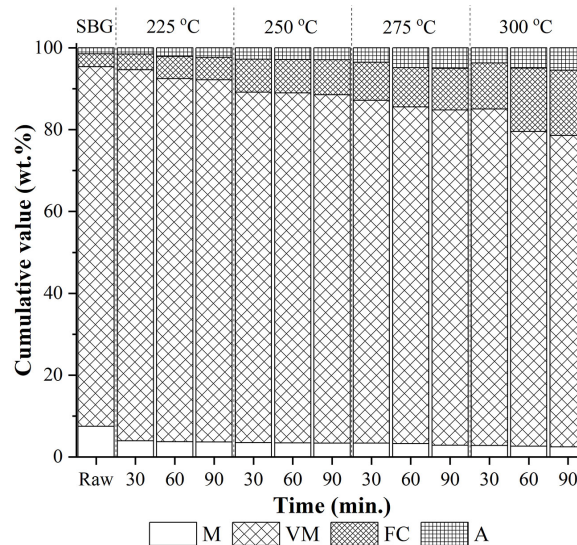

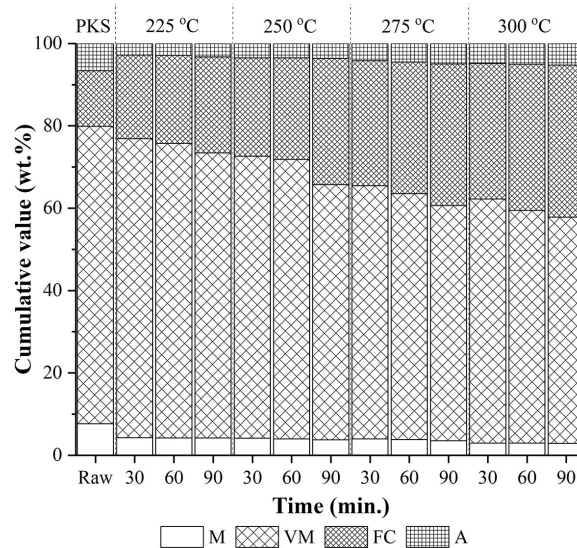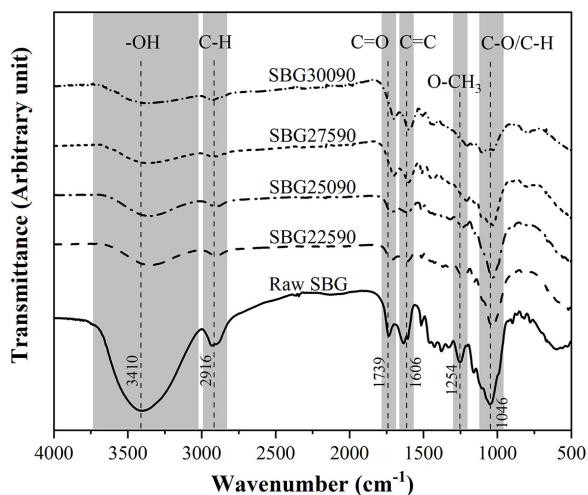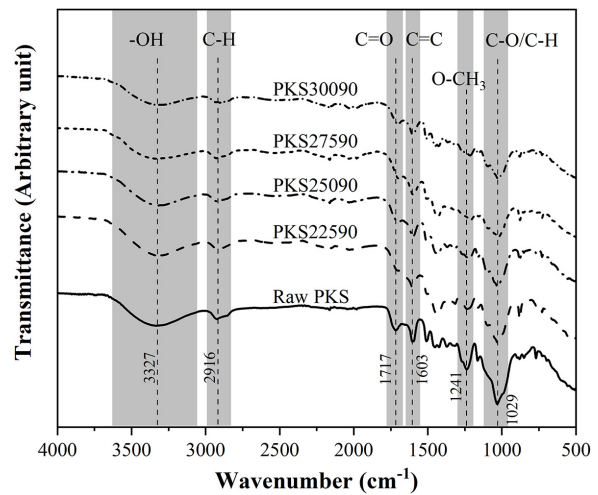**Figure 9.** Proximate analysis of untreated and torrefied sugarcane bagasse

Figure 10. Proximate analysis of untreated and torrefied palm kernel shell

et al., 2020; Putra et al., 2021]. The FTIR spectra of untreated and torrefied biomass produced by torrefaction pretreatment at different operating temperatures and constant residence time, i.e., 90 minutes, are shown in Figures 11 and 12. Altogether, the FTIR analysis results demonstrate that the intensities of the distinctive peaks of materials are decreased after torrefaction pretreatment as a result of the thermal degradation behavior of each lignocellulosic component. The very strong broad peaks at wavenumbers between 3,020 and 3,740 cm^{-1} are caused by the O-H bond related to the stretching vibration of the carbonyl and hydroxyl groups. The intensity of these peaks decreases as the torrefaction temperature rises, showing that carbonyl and hydroxyl groups are removed via decarboxylation and dehydration processes. The transmittance peaks recorded at roughly 2,916 cm^{-1} are ascribed to the C-H bond vibrational stretching in aliphatic and aromatic compounds. The reduction of C-H transmittance intensities suggests the aliphatic regions of hemicellulose and cellulose degradations. The transmittance peaks seen at roughly 1,660–1,780 cm^{-1} are referred to as C=O stretching vibration found in carbonyl and carboxyl groups in hemicellulose and cellulose structures. Decreasing in C=O transmittance intensities of torrefied biomass suggests that some hemicellulose and cellulose structures are destroyed as a result of decarbonylation and decarboxylation processes. The transmittance peaks observed between 1,200 and 1,300 cm^{-1} are connected with lignin's stretching vibration of the C=C or benzene ring skeleton, with a decrease in this signal representing lignin

Figure 12. FTIR spectra of untreated and torrefied palm kernel shell

degradation. Peaks at wavenumbers 960 and 1,130 cm^{-1} correspond to the stretching vibrations of C-O and C-H in cellulose, with a reduction in these groups indicating cellulose breakdown of the amorphous component.

The optimal condition for torrefaction

Various indicators, e.g., mass yield and calorific value, enhancement factor, energy yield, and energy gain, have been studied to establish the optimal condition for solid fuel pretreatment via the torrefaction process. Asadullah and coworkers (2014) reported that the temperature that produced bio-coal from PKS torrefaction with around 70% yield is an optimal torrefaction temperature. At an optimal torrefaction temperature of 300 °C with a residence period of 20 minutes, a yield of bio-coal of about 73% with a calorific value of 24.5 MJ/kg was attained [Asadullah et al., 2014]. Essentially, the enhancement factor refers to the proportion of torrefied biomass to raw biomass when comparing gross calorific values. Many authors reported that the attained optimal condition for biomass torrefaction yields an enhancement factor of around 1.3–1.4. Ibitoye et al. (2021) stated that a corncob that was torrefied at 260 °C for 60 minutes with an enhancement factor of 1.34 demonstrated the best thermal and combustion properties [Ibitoye et al., 2021]. In turn, Tsai et al. (2021) claimed that for the pretreatment of rice husk [Tsai et al., 2021] and *Sapindus* pericarp [Tsai et al., 2021], the appropriate torrefaction conditions may be found at roughly 280 °C (30 min) and 360 °C (0 min), with the

Figure 11. FTIR spectra of untreated and torrefied sugarcane bagasse

enhancement factor being 1.36 and 1.41, respectively. One of the criteria used to identify the optimal torrefaction condition is the energy yield, which is defined as the amount of original energy content that retains in the torrefied solid product. According to the majority of the literature, energy yield decreases as torrefaction becomes more severe. As a result, 75 to 90% is thought to be the accepted range for energy yield as described in the literature [Sabil et al., 2013; Ahmad et al., 2019; Aepia et al., 2021]. For the determination of the optimal torrefaction conditions for eucalyptus-tree residues, Cardona et al. (2019) proposed the use of a variable energy gain instead of energy yield, which provides a better compromise between mass and energy content. They suggested that a temperature of 275 or 300 °C and a residence time of 60 minutes, which gave high values of energy gain between 61–63, was the optimal condition depending on the applications of the product [Cardona et al., 2019]. Besides

that, an energy-mass co-benefit index (EMCI) describing the gap between the energy yield and the solid yield has been utilized to achieve the optimal conditions [Lu et al., 2012; Zhang et al., 2019; Devaraja et al., 2022]. A greater EMCI indicates a lesser volume of torrefied biomass and a higher energy density, both of which are favorable for the transportation and storage of fuel. For instance, based on the calculated EMCI it is reported that the torrefaction temperature at 275 °C and 60 min and 300 °C and 60 min are the favorable torrefaction conditions for Rubberwood and Gliricidia, respectively [Devaraja et al., 2022]. In order to identify the ideal circumstances for agro-byproduct torrefaction, Sunyong Park et al. (2020) employed energy yield, lower heating value, exergy, and criteria applicable to the biomass power plants in Korea. According to their findings, 230 °C, 40 and 50 minutes were the appropriate temperature and residence times for agro-pellet torrefaction. [Park et al., 2020].

Table 3. Enhancement factor, energy yield, energy gain, and energy-mass co-benefit index of torrefied solid products

Sample code	Enhancement factor	Energy yield (%)	Energy gain (%)	Energy-mass co-benefit index
Sugarcane bagasse torrefaction				
SBG22530	1.16	89.64	69.31	12.06
SBG22560	1.17	86.29	65.46	12.73
SBG22590	1.20	86.28	71.90	14.60
SBG25030	1.20	80.25	60.31	13.35
SBG25060	1.22	81.39	66.75	14.86
SBG25090	1.26	79.22	70.08	16.36
SBG27530	1.30	71.95	67.83	16.78
SBG27560	1.36	70.54	74.87	18.69
SBG27590	1.47	73.93	94.35	23.59
SBG30030	1.36	62.37	65.87	16.36
SBG30060	1.40	60.40	69.78	17.13
SBG30090	1.54	65.85	93.73	22.96
Palm kernel shell torrefaction				
PKS22530	1.10	92.17	60.05	8.01
PKS22560	1.14	93.54	77.12	11.23
PKS22590	1.15	92.72	76.98	11.97
PKS25030	1.15	85.65	58.14	11.01
PKS25060	1.16	84.31	58.98	11.74
PKS25090	1.18	84.94	60.20	12.66
PKS27530	1.19	75.33	52.39	12.20
PKS27560	1.24	76.03	61.27	14.51
PKS27590	1.28	77.41	70.75	16.91
PKS30030	1.29	69.86	62.77	15.58
PKS30060	1.29	69.42	62.69	15.58
PKS30090	1.30	68.74	64.16	15.99

Table 3 shows the torrefaction performance parameters, including enhancement factor, energy yield, energy gain, and energy-mass co-benefit index, obtained from this study. In accordance with the computed results, the enhancement factor and the energy-mass co-benefit index tend to improve while the energy yield tends to decline as torrefaction severity increases. No trend is observed for energy gain with the torrefaction condition pretreatment. Although the torrefied SBG and torrefied PKS exhibit high energy yield values (86.28–93.54%) when pretreated at 225 °C, the calorific values are still too low (18.29–20.84 MJ/kg), suggesting that these conditions are ineligible. Despite a high value of energy gain with 77.12% for PKS torrefied at 225 °C, the higher heating value of such torrefied PKS is quite low (20.63 MJ/kg). By integrating all criteria, it can be pointed out that the optimal condition for SBG as well as PKS torrefactions is the temperature of 275 °C for 90 minutes, acquiring the mass yield of 50.34 wt.% and 60.50 wt.% with the calorific value of 23.25 MJ/kg and 23.22 MJ/kg, respectively. Practically, the torrefaction of SBG and PKS could be performed at the temperature of 300 °C for 30 minutes, shorter holding time than that of 275 °C, to obtain a higher energy efficiency. Notably, both torrefied agro-industrial wastes obtained from such pretreatment conditions possess a high calorific value relative to coal (about 24 MJ/kg), suggesting that they could be utilized as a fuel for co-firing system.

CONCLUSIONS

Both SBG and PKS, abundant Thai agro-industrial wastes, upgraded via torrefaction technique constitute a promising solid fuel candidate which could be utilized for heat and power applications. According to the findings of the influence of operating condition inquiry, the torrefaction temperature is a more sensitive parameter than the residence duration in terms of mass yield, calorific value, and solid product characteristics. The results of the proximate analysis demonstrate that as the severity of torrefaction increases, the volatile matter of torrefied products decreases while the fixed carbon and ash contents increase. In addition, the torrefaction temperature and holding time tend to cause the FR values of torrefied SBG (0.04–0.14) and torrefied PKS (0.28–0.67) to increase exponentially. The FTIR analysis reveals that the chemical structures of hemicellulose, cellulose as well as lignin are changed, indicating the thermal degradation behavior of an individual component during the torrefaction pretreatment.

Even though the light torrefaction pretreatment conditions (225 and 250 °C) exhibited high values of mass yields and energy yields, these operating conditions are not recommended due to providing the low calorific values of the torrefied solid product. On the basis of the calorific value, energy yield, energy gain, and energy-mass co-benefit index, the optimal operating conditions for SBG and PKS torrefactions are reported at the torrefaction temperature of 275 °C and 90 minutes residence time, which could be enhanced by the calorific value from 15.83 MJ/kg to 23.25 MJ/kg and from 18.15 MJ/kg to 23.22 MJ/kg for SBG and PKS, respectively.

Regarding experimental data, this research serves as a starting point for biomass waste upgrading which could be used for energy production. The combustion efficiency of a coal/torrefied biomass co-combustion system would be assessed for further research in an attempt to reduce the coal usage in any coal-based thermal power plant.

REFERENCES

1. Ahmad R., Ishak M.A.M., Kasim N.N., Ismail K. 2019. Properties and thermal analysis of upgraded palm kernel shell and Mukah Balingian coal. Energy, 167, 538–547.

2. Arpia A.A., Chen W.H., Ubando A.T., Tabatabaei M., Lam S.S., Culaba A.B., De Luna M.D.G. 2021. Catalytic microwave-assisted torrefaction of sugarcane bagasse with calcium oxide optimized via Taguchi approach: Product characterization and energy analysis. Fuel, 305, 121543.

3. Asadullah M., Adi A.M., Suhada N., Malek N.H., Saringat M.I., Azdarpour A. 2014. Optimization of palm kernel shell torrefaction to produce energy densified bio-coal. Energy Conversion and Management, 88, 1086–1093.

4. Aslam U., Ramzan N., Aslam Z., Iqbal T., Sharif S., Hasan S.W.U., Malik A. 2019. Enhancement

of fuel characteristics of rice husk via torrefaction process. Waste Management and Research, 37(7), 737–745.

5. Basu P. 2013. Biomass gasification, pyrolysis, and torrefaction: Practical design and theory. Academic Press, Elsevier Inc.

6. Cardona S., Gallego L.J., Valencia V., Martínez E., Rios L.A. 2019. Torrefaction of eucalyptus-tree residues: A new method for energy and mass balances of the process with the best torrefaction conditions. Sustainable Energy Technologies and Assessments, 31, 17–24.

7. Chen W.H., Ye S.C., Sheen H.K. 2012. Hydrothermal carbonization of sugarcane bagasse via wet torrefaction in association with microwave heating. Bioresource technology, 118, 195–203.

8. Chen W.H., Liu S.H., Juang T.T., Tsai C.M., Zhuang Y.Q. 2015. Characterization of solid and liquid products from bamboo torrefaction. Applied Energy, 160, 829–835.

9. Chen W.H., Lin B.J., Lin Y.Y., Chu Y.S., Ubando A.T., Show P.L., Ong H.C., Chang J.S., Ho S.H., Culaba A.B., Pétrissans, A., Pétrissans, M. 2021. Progress in biomass torrefaction: Principles, applications and challenges. Progress in Energy and Combustion Science, 82, 100887.

10. Dai L., Wang Y., Liu Y., Ruan R., He C., Yu Z., Jiang L., Zeng Z., Tian X. 2019. Integrated process of lignocellulosic biomass torrefaction and pyrolysis for upgrading bio-oil production: A state-of-the-art review. Renewable and Sustainable Energy Reviews, 107, 20–36.

11. Devaraja U.M.A., Senadheera S.S., Gunarathne D.S. 2022. Torrefaction severity and performance of Rubberwood and Gliricidia. Renewable Energy, 195, 1341–1353.

12. Du S.W., Chen W.H., Lucas J.A. 2014. Pretreatment of biomass by torrefaction and carbonization for coal blend used in pulverized coal injection. Bioresource Technology, 161, 333–339.

13. Dyjakon A., Noszczyk T., Smędzik M. 2019. The influence of torrefaction temperature on hydrophobic properties of waste biomass from food processing. Energies, 12(24), 4609.

14. Dyjakon A., Noszczyk T. 2020. Alternative fuels from forestry biomass residue: Torrefaction process of horse chestnuts, oak acorns, and spruce cones. Energies, 13(10), 2468.

15. Faizal H.M., Jusoh M.A.M., Rahman M.R.A., Syahrullail S., Latiff Z.A. 2016. Torrefaction of palm biomass briquettes at different temperature. Jurnal Teknologi, 78(9–2), 61–67.

16. Granados D.A., Ruiz R.A., Vega L.Y., Chejne F. 2017. Study of reactivity reduction in sugarcane bagasse as consequence of a torrefaction process. Energy, 139, 818–827.

17. Ibitoye S.E., Jen T.C., Mahamood R.M., Akinlabi E.T. 2021. Improving the combustion properties of corncob biomass via torrefaction for solid fuel applications. Journal of Composites Science, 5(10), 260.

18. Ikubanni P.P., Oki M., Adeleke A.A., Adediran A.A., Adesina O.S. 2020. Influence of temperature on the chemical compositions and microstructural changes of ash formed from palm kernel shell. Results in Engineering, 8, 100173.

19. Inayat A., Inayat M., Shahbaz M., Sulaiman S.A., Raza M., Yusup S. 2020. Parametric analysis and optimization for the catalytic air gasification of palm kernel shell using coal bottom ash as catalyst. Renewable Energy, 145, 671–681.

20. Jagodzińska K., Czerep M., Kudlek E., Wnukowski M., Yang W. 2019. Torrefaction of wheat-barley straw: Composition and toxicity of torrefaction condensates. Biomass and Bioenergy, 129, 105335.

21. Kanwal S., Chaudhry N., Munir S., Sana H. 2019. Effect of torrefaction conditions on the physicochemical characterization of agricultural waste (sugarcane bagasse). Waste Management, 88, 280–290.

22. Li Z., Yi W., Li Z., Tian C., Fu P., Zhang Y., Zhou L., Teng J. 2020. Preparation of solid fuel hydrochar over hydrothermal carbonization of red jujube branch. Energies, 13(2), 480.

23. Lu K.M., Lee W.J., Chen W.H., Liu S.H., Lin T.C. 2012. Torrefaction and low temperature carbonization of oil palm fiber and eucalyptus in nitrogen and air atmospheres. Bioresource technology, 123, 98–105.

24. Ma Z., Zhang Y., Shen Y., Wang J., Yang Y., Zhang W., Wang S. 2019. Oxygen migration characteristics during bamboo torrefaction process based on the properties of torrefied solid, gaseous, and liquid products. Biomass and Bioenergy, 128, 105300.

25. Manatura, K. 2020. Inert torrefaction of sugarcane bagasse to improve its fuel properties. Case Studies in Thermal Engineering, 19, 100623.

26. Manouchehrinejad M., Mani S. 2018. Torrefaction after pelletization (TAP): Analysis of torrefied pellet quality and co-products. Biomass and Bioenergy, 118, 93–104.

27. Mayoral M.C., Izquierdo M.T., Andrés J.M., Rubio B. 2001. Different approaches to proximate analysis by thermogravimetry analysis. Thermochimica Acta, 370(1–2), 91–97.

28. Niu Y., Lv Y., Lei Y., Liu S., Liang Y., Wang D., Hui S. 2019. Biomass torrefaction: properties, applications, challenges, and economy. Renewable and Sustainable Energy Reviews, 115, 109395.

29. Park S., Kim S.J., Oh K.C., Cho L.H., Kim M.J., Jeong I.S., Lee C.G., Kim D.H. 2020. Characteristic analysis of torrefied pellets: Determining optimal

torrefaction conditions for agri-byproduct. Energies, 13(2), 423.

30. Putra H.E., Djaenudin D., Damanhuri E., Dewi K., Pasek A.D. 2021. Hydrothermal carbonization kinetics of lignocellulosic municipal solid waste. Journal of Ecological Engineering, 22(3), 188–198.

31. Ren X., Sun R., Meng X., Vorobiev N., Schiemann M., Levendis Y.A. 2017. Carbon, sulfur and nitrogen oxide emissions from combustion of pulverized raw and torrefied biomass. Fuel, 188, 310–323.

32. Rokni E., Ren X., Panahi A., Levendis, Y.A. 2018. Emissions of SO_2, NO_x, CO_2, and HCl from Co-firing of coals with raw and torrefied biomass fuels. Fuel, 211, 363–374.

33. Sabil, K.M., Aziz, M.A., Lal, B., Uemura, Y., 2013. Effects of torrefaction on the physiochemical properties of oil palm empty fruit bunches, mesocarp fiber and kernel shell. Biomass and Bioenergy, 56, 351–360.

34. Strandberg M., Olofsson I., Pommer L., Wiklund-Lindström S., Åberg K., Nordin A. 2015. Effects of temperature and residence time on continuous torrefaction of spruce wood. Fuel Processing Technology, 134, 387–398.

35. Sukiran M.A., Abnisa F., Daud W.M.A.W., Bakar N.A., Loh S.K. 2017. A review of torrefaction of oil palm solid wastes for biofuel production. Energy Conversion and Management, 149, 101–120.

36. Sukiran M. A., Abnisa F., Syafiie S., Daud W.M.A.W., Nasrin A.B., Aziz A.A., Loh S.K. 2020. Experimental and modelling study of the torrefaction of empty fruit bunches as a potential fuel for palm oil mill boilers. Biomass and Bioenergy, 136, 105530.

37. Tsai W.T., Jiang T.J., Tang M.S., Chang C.H., Kuo T.H. 2021. Enhancement of thermochemical properties on rice husk under a wide range of torrefaction conditions. Biomass Conversion and Biorefinery, 1–10.

38. Tsai W.T., Jiang T.J., Lin Y.Q., Zhang X., Yeh K.S., Tsai C.H. 2021. Fuel properties of torrefied biomass from *Sapindus* pericarp extraction residue under a wide range of pyrolysis conditions. Energies, 14(21), 7122.

39. Xu J., Huang M., Hu Z., Zhang W., Li Y., Yang Y., Shou Y, Shou S., Ma Z. 2021. Prediction and modeling of the basic properties of biomass after torrefaction pretreatment. Journal of Analytical and Applied Pyrolysis, 159, 105287.

40. Yang H., Yan R., Chen H., Lee D.H., Zheng, C. 2007. Characteristics of hemicellulose, cellulose and lignin pyrolysis. Fuel, 86(12–13), 1781–1788.

41. Yanik J., Duman G., Karlström O., Brink A. 2018. NO and SO_2 emissions from combustion of raw and torrefied biomasses and their blends with lignite. Journal of Environmental Management, 227, 155–161.

42. Zhang C., Ho S.H., Chen W.H., Fu Y., Chang J.S., Bi X. 2019. Oxidative torrefaction of biomass nutshells: Evaluations of energy efficiency as well as biochar transportation and storage. Applied Energy, 235, 428–441.