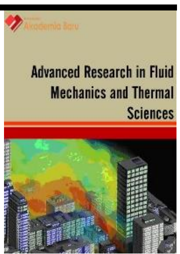
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



Torrefaction of Briquettes Made of Palm Kernel Shell with Mixture of Starch and Water as Binder

Open Access

Muhammad Ariff Hanaffi Mohd Fuad[1], Mohamad Muslihuddin Razali[1], Zaitul Nadiah Mohamad Izal[1], Hasan Mohd Faizal[1,2,*], Norhayati Ahmad[1,3], Mohd Rosdzimin Abdul Rahman[4], Md. Mizanur Rahman[1]

[1] School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[2] Automotive Development Centre (ADC), Institute for Vehicle System and Engineering, School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[3] Department of Material Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[4] Department of Mechanical Engineering, Faculty of Engineering, Universiti Pertahanan Nasional Malaysia, Kem Sg. Besi, 57000, Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 23 December 2019
Received in revised form 26 February 2020
Accepted 27 February 2020
Available online 26 April 2020

ABSTRACT

This study presents physical and combustion properties of briquettes made of palm kernel shell (PKS) with mixture of starch and water as binder. The briquettes with weight ratio of 60:40 (PKS: starch binder) were torrefied at various temperatures (225-275°C) and nitrogen flow rates (1000-3000 mL/min). The physical properties such as appearance, compressive strength, density and mass yield as well as combustion properties such as high heating value (HHV), energy yield and proximate analysis of untorrefied and torrefied briquettes were determined in the present study. The performances of the torrefied briquettes were also compared with the case of untorrefied briquettes as well as international benchmarks. It was found that torrefaction temperature significantly affects the properties of torrefied briquette rather than volume flow rate of nitrogen. At severe torrefaction condition (temperature of 275℃), HHV of 22.16±0.23 MJ/kg was obtained, that is the highest if compared to HHV of the briquettes torrefied at other temperatures. It was found that properties of the torrefied briquettes do not really affected by nitrogen flow rate. Overall, with the presence of starch binder, briquettes with considerably high compressive strength were obtained if compared to the previously developed binderless PKS briquettes.

Keywords:
Palm kernel shell; starch binder; torrefaction; briquette; temperature effect; flow rate effect

---

[*] *Corresponding author.*
E-mail address: mfaizal@mail.fkm.utm.my (Hasan Mohd Faizal)

https://doi.org/10.37934/arfmts.70.2.2136

1. Introduction

Depletion of global coal sources, environmental and health issues are major limitations for the energy industries to cope with the needs of high energy demand. According to National Emission Inventory (2014) [1], coal combustion alone can contribute up to 2862 tonnes of toxicity gases per year, thus leading to the environmental and health problems globally. Therefore, global coal sources that being used since 1973 [2] can be substituted by various alternative fuels.

Biomass based fuels offer promising benefits due to "clean", high energy potentiality and availability. Biomass-based fuels cover wide range of sources; from agricultural wastes to municipal solid wastes. Malaysia, being one of the world dominant oil palm producers, oil palm wastes are the highest commodity produced throughout the year, with around 56.45 million tonnes of wastes were generated annually from various parts of palm trees [3]. The palm wastes majorly consisted of 18.88 million tonnes of empty fruit bunch (EFB), 11.59 million tonnes of mesocarp fibre (MSF), 4.72 million tonnes of palm kernel shell (PKS), 17.10 million tonnes of trunk and 4.16 million tonnes of frond [3]. Due to large amount of wastes available, it is currently being used in multiple applications; manufacturing, agricultural, and energy production sectors [4,5]. In the energy perspective, oil palm wastes are considered as carbon-based wastes and potentially to be used in energy production sector due to the considerable amount of carbon content and energy content, that are approximately 46 to 58% and 16 to 20MJ/kg, respectively [6]. Among the oil palm wastes, raw PKS has the highest carbon and energy contents, that are 58% and 20 MJ/kg, respectively [6]. However, the aforementioned contents are still uncompetitive and unreadily used commercially if compared to coal. Therefore, combined pretreatments; densification and torrefaction can be implemented to convert raw PKS into a solid fuel with a high energy density [7]. Here, energy density is known as the amount of energy that contained in a unit volume of the densified products.

Densification (or compaction) is a conversion process of any loose materials into highly dense and durable products through compaction at high pressure [8,9]. In addition, densification allows proper utilization of loose materials or wastes and is beneficial to the logistic purposes. Due to the flexibility, densification process is implemented for wide range of applications; energy productions [10], building [11], pharmaceutical [12], and electrical industries [13]. In the case of energy production, generally, biomass is densified in prior to the end-use purposes. However, the physical quality (i.e physical strength, durability, water absorption) of densified biomass especially made of PKS is still unsatisfactory, thus adding binder is expected could address the issue.

Development of oil palm biomass based briquette has been initiated by Husain, Zainac and Abdullah [10], by using mixture of palm fibre and palm kernel shell. In general, excessively high compaction pressures that range from 150-800 MPa have been used for studies of densification of biomass as well as for commercialization [14,15] for obtaining high quality products. Thus, the scenarios, in turn making the densification process as an uneconomical process due to large energy consumption; for example, biomass pellets produced from compaction pressure of 158 MPa had consumed energy of about 56.8 MJ/t [15]. Due to this fact, many efforts have been performed until now in order to produce oil palm briquettes with high quality as well as economically viable.

The effect of various parameters such as compaction pressure, composition, type of binder as well as size of particles on the performance of briquettes have been studied previously [16,17]. Briquettes made of PKS has drawn attentions from number of parties such as industries and researchers due to the substantial amount of energy obtained during combustion. Besides, the presence of high composition of lignin [17] in PKS has potential to become as a source of binder for high quality briquette development. A study revealed that the thermally heated briquetting can produce physically strong oil palm briquettes with average compressive strength of 7.9MPa, thus showing the potential of lignin to become as a binder, and therefore, adding additional binder is expected can further enhance the physical strength of the briquettes [18].

On the other hand, as an alternative to the thermally heated process during briquetting, the use of additional binder could be a potential alternative. Interestingly, the additional binder could be made of readily available sources derived from organic (i.e natural sources) and inorganic (synthetic sources) by-products [17]. Generally, natural sources are environmentally friendly [12] rather than synthetic sources which are more hazardous [19]. Both sources of binder have been used and tested by many researchers and the results demonstrated the possibility of producing durable and high density briquette, ranging from 1 to 14 MPa of compressive strength and 820 to 1137kg/m3 of mass density [15,17,19–25]. For the case of the natural binder, the mixture of PKS bio-char and starch briquette has been developed [23]. Interestingly, the study has shown the presence of starch binder played an important role in making a durable PKS briquette [23]. Based on their study, they obtained 821±26 kN/m2 of tensile crushing strength and 167 of impact resistance index (IRI) [23]. However, the study had revealed that the briquette achieves a considerably low water resistance index of less than 50%, revealing that the briquette with starch binder is more hygroscopic, and this phenomenon could degrade the combustion performance as well as inconvenience for logistic activities (handling, storage and transportation) [23]. Interestingly, by torrefaction, the aforementioned problem could be potentially addressed so that the products have potential to become more hydrophobic nature [26,27].

Meanwhile, torrefaction is known for its capability to enhance the combustion properties of raw biomass, to some extent become superior properties than that of coal [26]. Interestingly, torrefaction offers improvement at mild reaction; temperature range of 200 to 300°C with heating rate of ≤50°C/min [28]. Torrefaction is typically performed in an inert environment with mild (200-250°C) or severe (250-300°C) torrefaction conditions [29]. In both torrefaction conditions, degradation of lignocellulose components of biomass occurs [30], resulting the formation of various energy sources; bio-char, bio-oils and non-condensable gases. In addition, sufficiently high amount of energy obtained from severe reaction has been reported to be suitable for energy production sector [31]. In addition, it is interesting to note that the syngas obtained from gasification of torrefied biomass has considerably higher quality if compared to the syngas obtained from gasification of raw biomass [32]. Based on the advantages as mentioned above, solid products obtained from torrefaction have potential to be used as coal replacement.

Combined pretreatments of densification (with additional binder) followed by torrefaction becomes as state-of-the-art of the present study. The study on combined pretreatments has not been performed yet for the case of PKS with starch binder, even though numerous studies on the combined densification and torrefaction of biomass have been widely published. The previous studies on combined densification and followed by torrefaction or vice versa have shown a significant improvement in terms of the quality of biomass pellets or briquettes due to the torrefaction effect [7,26,27,33,34]. Besides, in torrefaction, biomass briquettes with relatively high energy content (25.5 to 29.6 MJ/kg) [20,26,35,36] and carbon content up to 63.3% [26] have been produced. In the other studies, the torrefied biomass briquettes with considerably high durability (i.e high compressive strength with the range of 1.5 to 5MPa) were successfully developed [7,20,36]. During torrefaction, biomass briquettes suffer a severe mass loss as torrefaction temperature is increased, which in turn causes the density of biomass briquette to be slightly lower if compared to the untorrefied biomass briquette. A few studies have reported that the density of torrefied biomass briquettes are around 600 to 900 kg/m3 [7,20,36]. As mentioned previously, combined torrefaction and followed by densification could produce the physically strong and dense biomass pellets, however, large energy consumption used during densification have been reported [33,34]. A recent study has shown that binderless PKS briquette suffers a severe physical destruction when torrefaction is performed at severe condition [7]. Until now, there is no investigation on the potentiality of using PKS briquette with starch as binder for the combined pretreatments of densification and torrefaction to address the aforementioned problems.

The present study is performed to understand fundamentally physical and combustion properties of the PKS briquette containing starch binder (with weight ratio of 60:40) after torrefaction. The parameters involved were torrefaction temperature (225-275℃) and nitrogen flow rate (1000-3000 mL/min). Physical and combustion performances of briquettes were evaluated in terms of physical appearance, density, compressive strength, density yield and mass yield as well as energy yield, heating value, and proximate analysis. Furthermore, the performance of the produced briquettes in the present study were also compared with international benchmarks as well as previously produced binderless PKS briquette [7].

2. Materials Preparation and Methodology

2.1 Materials

The PKS was collected from a local oil palm mill and was pulverized by using crushing machine (RETSCH BB50). The pulverized PKS was then sieved to obtain particles with size of less than 500µm by using a sieve shaker machine (RETSCH type AS200 digit). Meanwhile, corn starch was purchased from a local supplier. The properties of materials are shown in Table 1. The moisture content and volatile matter of raw PKS were found to be lower than that of corn starch binder. Meanwhile, ash content, fixed carbon and high heating value of raw PKS are higher if compared to the corn starch binder.

Table 1
Properties of raw PKS and corn starch binder

	Raw PKS	Corn starch binder
Proximate analysis		
Moisture content (wt %)	10.75±0.00	77.35±0.56
Volatile matter (db %)[a]	75.81±0.00	96.98±0.36
Ash content (db %)[a]	3.79±0.00	0.22±0.22
Fixed carbon (db %)[a,b]	20.40±0.00	2.79±0.58
High heating value (MJ/kg)	17.88±0.02	1.31±0.33

[a] dry basis
[b] Calculated by difference

2.2 Gelatinization of Starch Binder and Briquetting

For preparation of starch binder, the distilled water and corn starch with weight ratio of 80:20 [35] were mixed and continuously stirred at stirring speed of 200 rpm for 10 minutes at room temperature to ensure the homogeneity of the mixture [37]. The mixture of starch and water were then gelatinized and continuously stirred at the same rated speed of 200rpm in a warm water with temperature of 75℃ for 30 minutes [12,38]. The gelatinized starch binder was left to be cooled inside a desiccator for a day in prior to mixing with pulverized PKS.

Then, the PKS and starch binder with weight ratio of 60:40 was mixed homogeneously by using a stand mixer (Model PM-215) at low speed (at level 1) for 30 minutes [39]. The mixing ratio of 60:40 was employed due to the promising abrasive resistance [40]. Based on this statement, 50g of the mixture of PKS and starch binder were loaded into a cylindrical stainless steel die set with internal diameter of 50 mm and the mixture was compressed at a fixed condition (compaction pressure of 7

MPa and holding time of 30 minutes) by using INSTRON 600 DX Universal Testing Machine. The produced briquette with diameter of around 50mm and height of 20mm was then left at an ambient condition for a week to achieve stability.

2.3 Torrefaction Of PKS and Starch Binder Briquette

In the present study, torrefaction was performed in a vertical reactor with internal diameter of 100mm as shown in Figure 1. The reactor was equipped with heater clamp on the outer surface of reactor as well as K-type thermocouple sensor. The K-type thermocouple sensor was set 3 mm above the briquette in the reactor. In this study, the briquette was torrefied for various torrefaction temperatures and nitrogen flow rates of 225℃ to 275℃ and 1000 to 3000 mL/min, respectively. Initially, the briquette was placed on the mesh holder and was put inside the reactor. The lid of reactor was sealed tightly. Later, the reactor was purged by designated nitrogen flow rates for one hour and subsequently the briquette was heated according to the desired torrefaction temperature for 30 minutes. Upon completion, the heater was set to 30℃ and the briquette was cooled under continuous flow of nitrogen. Finally, the briquette was taken out from the reactor and was left at an ambient condition for a week to ensure the stability and rigidity.

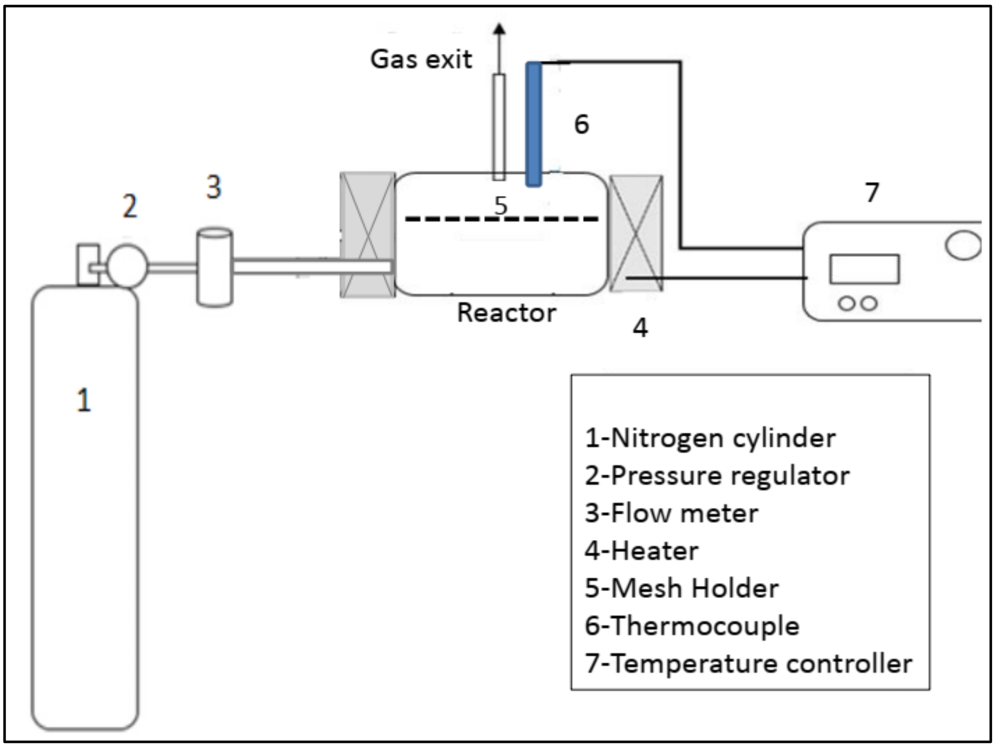


Fig. 1. The experimental setup of torrefaction [36]

2.4 Characterization

Proximate analysis of the untorrefied and torrefied briquettes were performed in accordance to the ISO standards; moisture contents (EN ISO 18134-2:2015) [41], volatile matter content (EN ISO 18123:2015) [42], and ash content (EN ISO 18122:2015) [43]. Meanwhile, high heating value was determined in accordance to ISO standards EN ISO 14918:2010 [44]. The heating values for the untorrefied and torrefied briquettes were determined by using IKA calorimeter system (model C2000).

In the present study, the relaxed density was also determined by measuring the mass and volume of the untorrefied and torrefied briquettes [45] while mass and energy yields were determined by following method introduced by Bridgeman *et al.,* [46] and Huang *et al.,* [47], respectively. The equation for determining density, mass and energy yields of briquettes are shown by Eq. (1)-(4). The characterization of the untorrefied and torrefied briquettes was repeated twice.

Relaxed density (kg/m^3) = mass (kg) / volume (m^3) (1)

Mass yield (%) = [(mass of torrefied briquette) / (mass of untorrefied briquette)] X 100 (2)

Density yield (%) = [(density of torrefied briquette) x 100
/ (density of untorrefied briquette)] (3)

Energy yield (%) = mass yield (%) x (heating value of torrefied biomass/heating value
of untorrefied biomass) × 100 (4)

2.5 Compressive Testing

In the present study, the compressive strength of the untorrefied and torrefied briquettes were tested by using INSTRON 100 kN Universal Testing Machine. The produced briquette was put on the centre of bottom plate of the compression machine. The top plate of the compression machine was then moved downward with a speed of 0.05 mm/sec to compress the briquette. The test was completed when the sudden drop of force (that representing the crack) was observed.

3. Results and Discussion

3.1 Effect of Torrefaction Temperature on Physical and Combustion Properties of Briquettes

Generally, temperature plays an important role in affecting physically and combustibility of torrefied products. The reaction becomes more severe as the temperature is increased. For investigation on the effect of temperature, the briquettes were torrefied under various torrefaction temperatures (225, 250 and 275°C) at a constant flow rate of nitrogen (1000 mL/min).

3.1.1 Physical appearance of torrefied briquettes

Figure 2 shows the physical appearance of briquettes that contained mixture of PKS and starch binder, torrefied under various torrefaction temperatures (225, 250 and 275°C) and at a constant flow rate of nitrogen (1000 mL/min). Here, the image of the untorrefied briquette is also enclosed. With an increase in torrefaction temperature, the physical condition of the torrefied briquettes was found to be slowly degraded (mild crack surface). This is mainly due to more intense reaction of torrefaction as the temperature is increased. Interestingly, the physical condition of the produced briquettes was considerably improved and sustained even after intensively torrefied at severe torrefaction condition if compared to the previously produced briquettes that suffered a mild and severe deterioration at torrefaction temperatures of 250°C and 275°C, respectively [7]. These findings revealed that the starch binder is hardened as it is thermally heated [17]. Meanwhile, the colour of the torrefied briquettes changed from light brownish to darker as torrefaction temperature is increased, indicating the increase of carbon content after torrefaction [26].

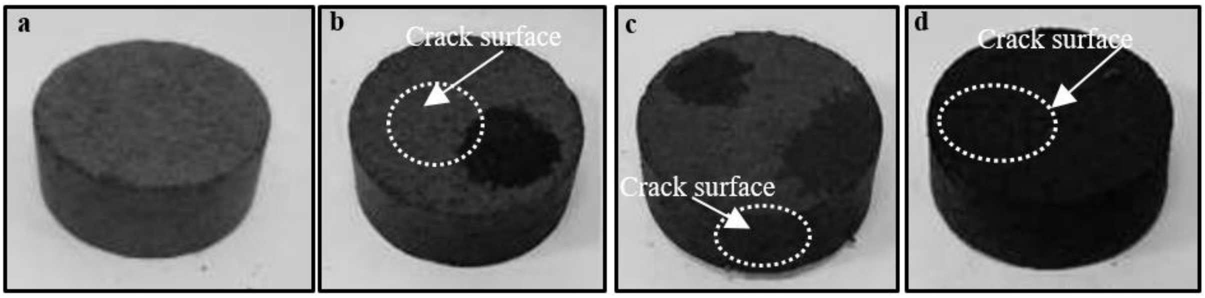


Fig. 2. Physical appearance of (a) untorrefied briquette, (b) briquette torrefied at 225℃, (c) briquette torrefied at 250℃ and (d) briquette torrefied at 275℃

3.1.2 Physical properties of torrefied briquettes

Figure 3 shows compressive strength of the torrefied briquettes produced under various torrefaction temperatures. It was found that the compressive strength decreases, ranging from around 9.61±1.20 to around 3.41±0.01 MPa when the torrefaction temperature is increased from 225 to 275℃. This phenomenon is mainly due to the more intense reaction as torrefaction temperature is increased, resulting in more severe physical degradation. This phenomenon is well agreement with other studies on torrefied briquette [7,20,36]. Interestingly, in the present study, the compressive strength of the produced torrefied briquettes regardless of torrefaction temperature were higher if compared to the strength of the untorrefied briquette (2.59±0.07 MPa) and the strength of the previously developed torrefied binderless PKS briquettes (0.8 to 2.5 MPa) [7], thus revealing the importance of starch binder in producing highly durable briquette [17]. Meanwhile, the densities of the torrefied briquettes (Figure 4) in the present study were found to be slightly lower if compared to the untorrefied briquette, with the range of around 846 to 753 kg/m^3.

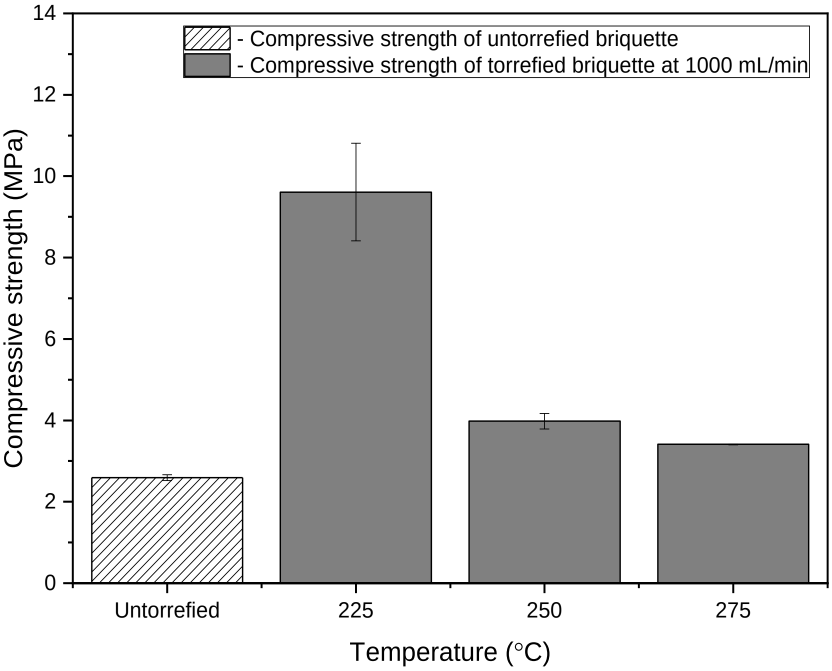


Fig. 3. Compressive strength of briquettes torrefied under various temperatures at nitrogen flow rate of 1000 mL/min

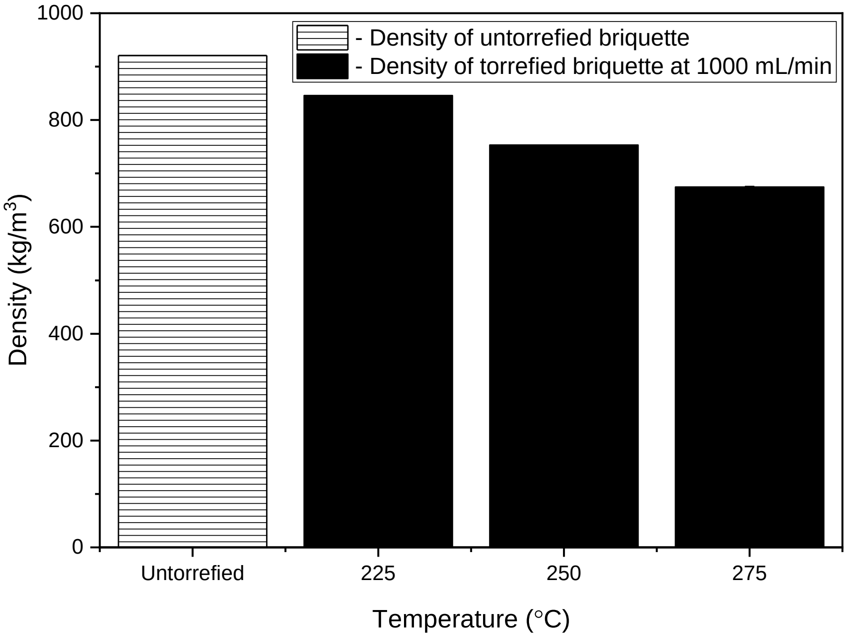


Fig. 4. Density of briquettes torrefied under various temperatures with fixed nitrogen flow rate of 1000 mL/min

3.1.3 Combustion properties of torrefied briquette

Figure 5 illustrates the density, mass and energy yields of briquettes torrefied under various torrefaction temperatures. In the present study, the density, mass and energy yields of the torrefied briquettes decrease from 92 to 73%, 84 to 59 % and 89 to 73%, respectively as the torrefaction temperature is increased from 225 to 275℃. The decreasing trend of density, mass and energy yields of the torrefied briquettes revealed that devolatilization becomes more rapid when the temperature is increased [26,34].

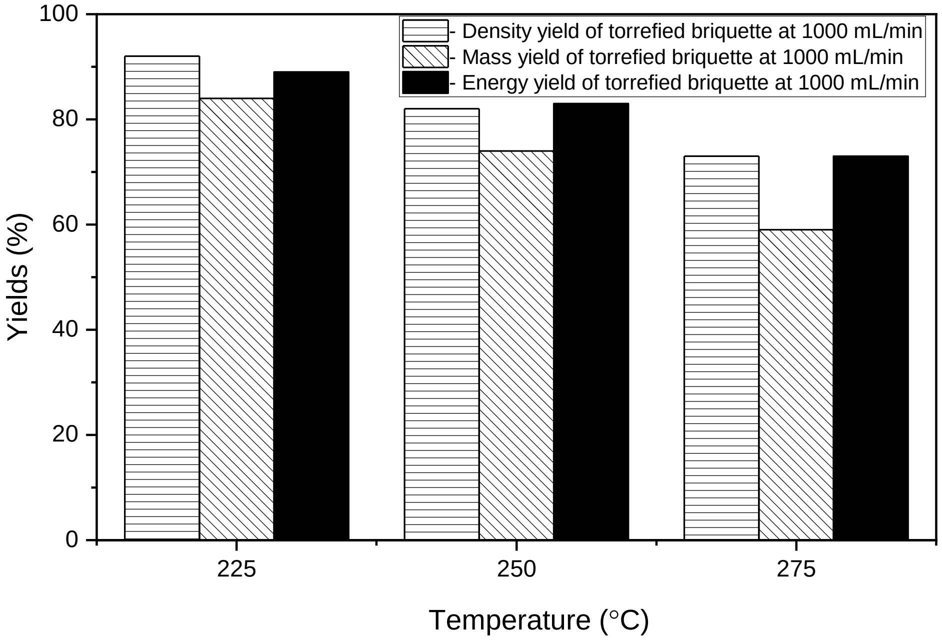


Fig. 5. Yields of briquettes torrefied under various temperatures and fixed nitrogen flow rate of 1000 mL/min

The high heating values (HHV) of the briquettes torrefied under various torrefaction temperatures are shown in Table 2. It could be observed that as the torrefaction temperature is increased, the HHV of the torrefied briquettes increases from 17.88±0.01 to 22.16±0.23 MJ/kg, thus implying an increase in carbon and fixed carbon contents. However, it was found that the HHV of the briquettes torrefied at 225℃ increases slightly, only about 6% if compared to the HHV of the untorrefied briquette due to mild decomposition phase. Based on the results obtained, it can be said that HHV of the torrefied briquettes produced are higher if compared to the HHV of the untorrefied briquettes. However, if compared to the previously developed torrefied binderless PKS briquette, the HHV of the torrefied briquettes in the present study was found to be slightly lower [7]. It was found that the performance still fulfils the requirements stated by international benchmarks. As comparison, at the same torrefaction temperature (i.e 275℃), HHV of the torrefied binderless PKS briquette [7] was 24.12 MJ/kg while HHV of the torrefied PKS briquette with starch binder in the present study was 22.16±0.23 MJ/kg. This phenomenon is supposed due to the high composition of starch binder, thus causing the produced torrefied briquettes in the present study tend to be more hygroscopic.

Table 2
Summary of fuel properties of untorrefied briquettes and briquettes torrefied under various torrefaction temperatures and nitrogen flow rates

Analysis	Conditions						International benchmark
	Untorrefied	225[a]	250[a]	275[a]	275[b]	275[c]	
Proximate analysis							
Moisture content (%)	10.75±0.00	8.01±0.00	6.73±0.24	6.88±0.78	6.54±0.24	6.59±0.39	<10%[d]
Volatile matter (db %)	75.81±0.00	74.04±0.00	68.42±0.42	57.67±0.76	59.62±0.86	62.42±0.09	
Ash content (db %)	3.79±0.00	4.92±0.00	4.89±0.15	6.53±1.11	6.94±0.75	7.26±0.02	<5%[e]
Fixed carbon (db %)	20.40±0.00	21.05±0.00	26.69±0.53	35.79±1.87	33.44±1.61	30.32±0.12	
High heating value (MJ/kg)	17.88±0.01	18.96±0.33	20.07±0.38	22.16±0.23	21.82±0.58	20.85±0.26	>20%[f]

[a] Briquette torrefied with flow rate of 1000 mL/min
[b] Briquette torrefied with flow rate of 2000 mL/min
[c] Briquette torrefied with flow rate of 3000 mL/min
[d] EN ISO 18134-2:2015[41]
[e] EN ISO 18122:2015 [43]
[f] EN ISO18125: 2017 [48]

The results of proximate analysis for the untorrefied briquettes and briquettes torrefied at various temperatures are shown in Table 2. In general, fixed carbon content of the torrefied briquettes in the present study increases from 20.40±0.00 to 35.79±1.87 db% when the torrefaction temperature is increased. Meanwhile, it was found that the volatile matter of the torrefied briquettes decreases from 74.04±0.00 to 57.67±0.76 db% when the torrefaction temperature is increased. On the other hand, the ash content of the torrefied briquettes produced under various torrefaction temperatures was found to be higher (within the range of 4.89±0.15 to 6.53±1.11 db%) if compared to the ash content of the untorrefied briquette (only 3.79±0.00 db%). However, it can be said that the ash content of the torrefied briquettes in the present study is still competitive if compared to the requirement stated by international benchmarks. The occurrence of this phenomena is due to the lower torrefaction temperatures employed in the present study if compared to the temperature of vaporization phase of alkali salts in ash [49,50]. In the present study, moisture content of the torrefied briquettes was found to be within the range of 6.73±0.24 to 8.01±0.00%. Generally, it can be said that the moisture content of the briquettes is reduced when the torrefaction pretreatment is applied due to the drying and vaporization processes. Overall, it was found that the moisture content of the torrefied briquettes produced in the present study fulfils the requirement as stated by EN ISO 18134-2:2015 (<10%) [41] while the ash content was found to be competitive if compared to the requirement as stated by EN ISO 18122:2015 (<5%) [43].

3.2 Effect of Nitrogen Flow Rate on Physical and Combustion Properties of Briquettes

In the present study, the effect of nitrogen flow rate on the physical and combustion properties of the briquettes was investigated at fixed torrefaction temperature of 275℃ and nitrogen flow rates of 1000 to 3000 mL/min.

3.2.1 Physical appearance of briquettes torrefied under various nitrogen flow rates

Figure 6 shows the physical appearance of the briquettes torrefied at 275℃ under various nitrogen flow rates. It was found that the colour of the briquettes torrefied at various nitrogen flow rates becomes darker after being torrefied. However, the darkness level was found to become mild once nitrogen flow rate is increased, thus revealing that the briquette may not fully carbonized. This is mainly due to the increasing volume flow rate of nitrogen gas that in turn leading to more unreactive atmosphere during torrefaction. This phenomenon is also observed by the previous researchers who performed torrefaction of oil palm frond for various flow rates (50 to 150 mL/min) [51]. Meanwhile, the briquettes torrefied at various flow rates (Figure 6) was considerably sturdy as only mild crack could be observed on the surface of the torrefied briquettes, thus revealing the hardening of binder takes place when the briquette is thermally heated [17].

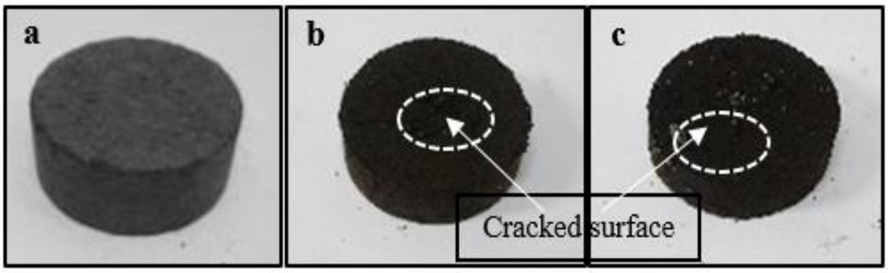


Fig. 6. Physical appearance of briquettes torrefied under various flow rates of nitrogen: (a) untorrefied briquette, (b) briquette torrefied at 2000 mL/min and (c) briquette torrefied at 3000 mL/min

3.2.2 Physical properties of torrefied briquettes for various flow rates

The compressive strength of the torrefied briquettes produced under various flow rates is illustrated in Figure 7. In the present study, it was found that the values of compressive strength of the torrefied briquettes exceed 4.8 MPa. If compared to the compressive strength of the untorrefied briquettes and briquettes torrefied at 275℃ under flow rate of 1000 mL/min, the strength of the briquettes after torrefaction under flow rate of 2000 mL/min was relatively higher. It can be said that the strength of the torrrefied briquette slightly increases when the flow rate is increased, showing that the briquettes somehow experience milder degradation due to more unreactive atmosphere. Based on the results obtained, it was found that torrefaction improves the compressive strength of the briquettes, in which the strength is enhanced by 30% to 80%. However, the trend of compressive strength with respect to nitrogen flow rate (between 2000 and 3000 mL/min) is unclear, that is supposed due to milder effect of nitrogen flow rate if compared to the effect of uncertainties involved when the briquettes experiencing significant physical destruction at torrefaction temperature of 275℃. Meanwhile, density of the briquettes (see Figure 8) ranged from 725.42 to 690.50 kg/m3 for torrefaction under various nitrogen flow rates, showing that briquettes are intensively volatilized during torrefaction.

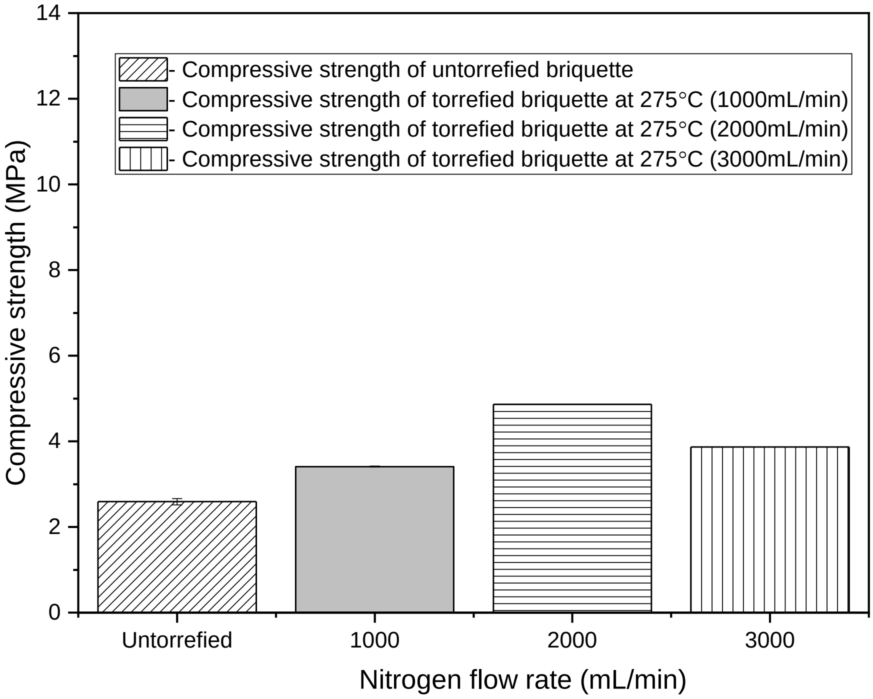


Fig. 7. Compressive strength of briquettes torrefied under various flow rates of nitrogen and fixed temperature of 275℃

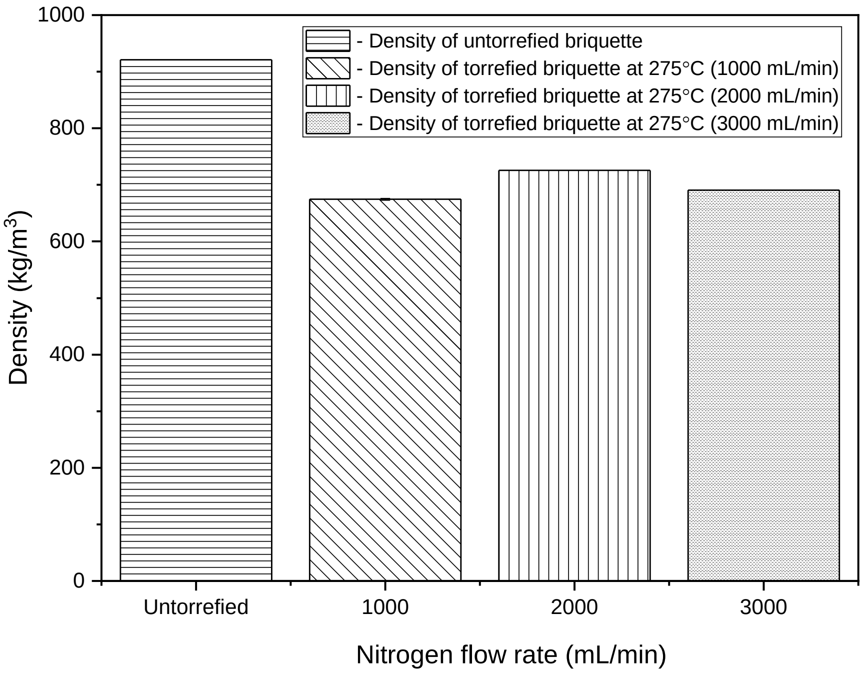


Fig. 8. Density of briquettes torrefied under various flow rates of nitrogen and fixed temperature of 275°C

3.2.3 Combustion properties of torrefied briquette for various nitrogen flow rates

The density, mass and energy yields of the produced briquettes torrefied under various flow rates are illustrated in Figure 9. In the present study, it was found that the density yield of the torrefied briquettes increases from 73 to 79% when the flow rate is increased from 1000 to 2000 mL/min, and slightly decreases to 75% when nitrogen flow rate is further increased to 3000 mL/min. Meanwhile, the mass yield of the torrefied briquettes increased from 60 to 64% with an increase in flow rate, proving that an increase in flow rate leads to more unreactive atmosphere during torrefaction. Meanwhile, energy yield of the torrefied briquettes was found to be within the range of 73 to 75%. If comparison is performed between the briquettes torrefied at different nitrogen flow rate, it can be said that there is almost no change in the energy yield but the mass yield and density yield change slightly. Similar findings on the insignificant changes of yields under various nitrogen flow rates have also been reported by several previous studies [35,52,53].

Table 2 shows the high heating value (HHV) of the untorrefied briquettes and briquettes torrefied under various flow rates of nitrogen. It could be observed that the heating value of the torrefied briquettes is higher if compared to the untorrefied briquettes. In the present study, the highest HHV obtained was about 21.82±0.58 MJ/kg for the briquettes torrefied at nitrogen flow rate of 2000 mL/min. However, when the flow rate was further increased to 3000 mL/min, the HHV of the torrefied briquettes slightly declined to 20.85 MJ/kg, thus proving that the environment for torrefaction becomes less reactive as the flow rate is increased. This phenomenon has also been reported in several studies [35,51]. Based on the proximate analysis of the torrefied briquettes, it was found that the fixed carbon content of the torrefied briquettes slightly decreases from 33.44±1.61to 30.32±0.12 db% when the flow rate is increased from 2000 to 3000 mL/min. Meanwhile, ash contents of the briquettes torrefied under flow rates of 2000 and 3000 mL/min were 6.94±0.75 and 7.26±0.02 db%, respectively, in which higher than that of the untorrefied briquettes, briquettes torrefied under flow rate of 1000 mL/min and international benchmarks. On the other hand, it was found that the volatile matter and moisture contents of the torrefied briquettes increase slightly from 59.62±0.86 to 62.42±0.09 db% and 6.54±0.24 to 6.59±0.39%, respectively with an increase in flow rate.

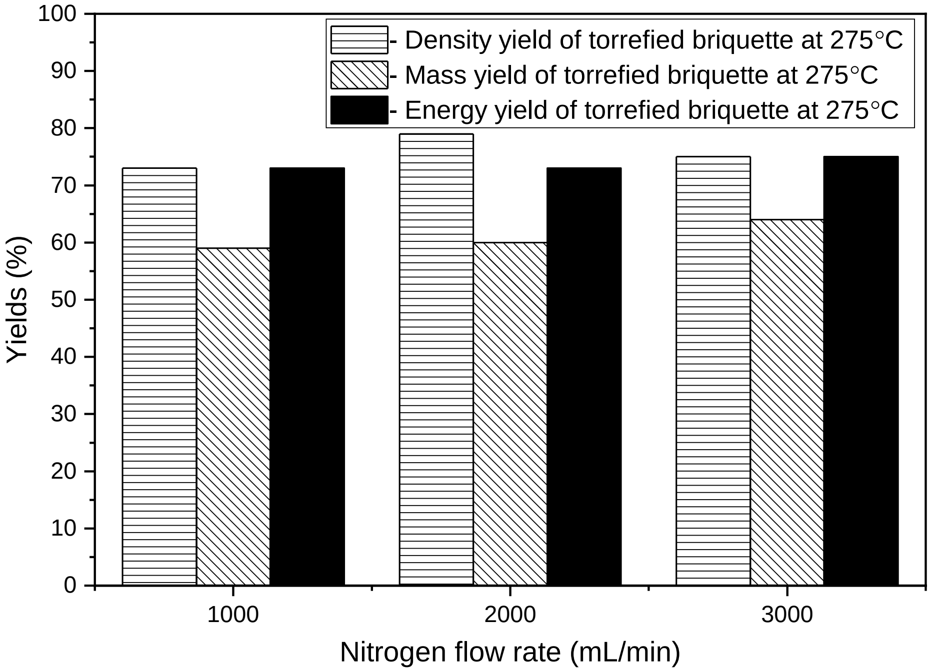


Fig. 9. Yields of briquettes torrefied under various flow rates of nitrogen and fixed temperature of 275℃

4. Conclusions

Briquettes made of mixture of PKS and starch binder have been developed and an investigation was performed to study the effect of torrefaction temperature and nitrogen flow rate on the physical and combustion properties of the torrefied products. In terms of the effect of temperature, it can be said that torrefaction temperature is a dominant factor for the changes in physical and combustion properties. When temperature is increased, the compressive strength, density and density yield of the torrefied briquettes decrease. In terms of combustion properties of the torrefied briquettes produced under various temperatures, the mass and energy yields decrease while moisture content, HHV, fixed carbon and ash content increase with increasing temperature.

For the case of briquettes torrefied under various flow rates of nitrogen, compressive strength, density and density yield somehow fluctuate with an increase in flow rate of nitrogen. It was also found that when flow rate of nitrogen is increased, the ash content, fixed carbon and HHV of the produced briquettes decrease. However, mass and energy yields as well as moisture content and volatile matter were found to increase with an increase in flow rate of nitrogen. Overall, in most cases, due to the presence of starch binder, durable torrefied briquettes with competitive combustion properties could be obtained.

Acknowledgement

The authors acknowledge the Ministry of Higher Education Malaysia, Malaysia and Universiti Teknologi Malaysia, Malaysia for giving cooperation and full support in this research activity. The authors wish to thank Research Management Center (RMC) for Tier 2 grant (VOT No.: Q.J130000.2651.16J28) from Ministry of Higher Education Malaysia and Universiti Teknologi Malaysia.

References

[1] U. S. Environmental Protection Agency. "2014 National Emissions Inventory, Version 2 Technical Support Document." *National Emissions Inventory*, 2018.

[2] Conti, John, Paul Holtberg, Jim Diefenderfer, Angelina LaRose, James T. Turnure, and Lynn Westfall. "International Energy Outlook 2016, With Projections to 2040. May 2016." *Washington, DC, USA: US Energy Information Administration (EIA),* 2016. https://doi.org/10.2172/1296780

[3] Malaysian Palm Oil Board (MPOB). "Malaysian Oil Palm Statistics 2016 36th Ed." *Malaysia: MPOB, Ministry of Plantation Industries and Commodities*, 2016.

[4] Sukiran, Mohamad Azri, Faisal Abnisa, Wan Mohd Ashri Wan Daud, Nasrin Abu Bakar, and Soh Kheang Loh. "A review of torrefaction of oil palm solid wastes for biofuel production." *Energy Conversion and Management* 149 (2017): 101-120. https://doi.org/10.1016/j.enconman.2017.07.011

[5] Sulaiman, Fauziah, Nurhayati Abdullah, Heiko Gerhauser, and Adilah Shariff. "A perspective of oil palm and its wastes." *Journal of Physical Science* 21, no. 1 (2010): 67-77.

[6] Loh, Soh Kheang. "The potential of the Malaysian oil palm biomass as a renewable energy source." *Energy Conversion and Management* 141 (2017): 285-298. https://doi.org/10.1016/j.enconman.2016.08.081

[7] Faizal, Hasan Mohd, Hielfarith Suffri Shamsuddin, M. Harif M. Heiree, Mohd Fuad Muhammad Ariff Hanaffi, Mohd Rosdzimin Abdul Rahman, Md Mizanur Rahman, and Z. A. Latiff. "Torrefaction of densified mesocarp fibre and palm kernel shell." *Renewable Energy* 122 (2018): 419-428. https://doi.org/10.1016/j.renene.2018.01.118

[8] Mitchual, Stephen J., Kwasi Frimpong-Mensah, and Nicholas A. Darkwa. "Effect of species, particle size and compacting pressure on relaxed density and compressive strength of fuel briquettes." *International Journal of Energy and Environmental Engineering* 4, no. 1 (2013): 30. https://doi.org/10.1186/2251-6832-4-30

[9] Cavallo, Eugenio, and Niccolò Pampuro. "Effects of compressing pressure on briquettes made from woody biomass." *Chemical Engineering Transactions* 58 (2017): 517-522.

[10] Husain, Z., Z. Zainac, and Z. Abdullah. "Briquetting of palm fibre and shell from the processing of palm nuts to palm oil." *Biomass and Bioenergy* 22, no. 6 (2002): 505-509. https://doi.org/10.1016/S0961-9534(02)00022-3

[11] Chen, Yongliang, Yimin Zhang, Tiejun Chen, Yunliang Zhao, and Shenxu Bao. "Preparation of eco-friendly construction bricks from hematite tailings." *Construction and Building Materials* 25, no. 4 (2011): 2107-2111. https://doi.org/10.1016/j.conbuildmat.2010.11.025

[12] Chitedze, Judith, Maurice Monjerezi, JD Kalenga Saka, and Jan Steenkamp. "Binding effect of cassava starches on the compression and mechanical properties of Ibuprofen tablets." *Journal of Applied Pharmaceutical Science* 2, no. 4 (2012): 31. https://doi.org/10.7324/JAPS.02.4.004

[13] Li, Huan, Ying Tao, Xiaoyu Zheng, Jiayan Luo, Feiyu Kang, Hui-Ming Cheng, and Quan-Hong Yang. "Ultra-thick graphene bulk supercapacitor electrodes for compact energy storage." *Energy & Environmental Science* 9, no. 10 (2016): 3135-3142. https://doi.org/10.1039/C6EE00941G

[14] Demirbaş, A. "Physical properties of briquettes from waste paper and wheat straw mixtures." *Energy Conversion and Management* 40, no. 4 (1999): 437-445. https://doi.org/10.1016/S0196-8904(98)00111-3

[15] Peng, Jianghong, Xiaotao T. Bi, C. Jim Lim, Hanchao Peng, Chang Soo Kim, Dening Jia, and Haibin Zuo. "Sawdust as an effective binder for making torrefied pellets." *Applied Energy* 157 (2015): 491-498. https://doi.org/10.1016/j.apenergy.2015.06.024

[16] Faizal, Hasan Mohd, Z. A. Latiff, and Muhammad Amin Mohd Iskandar. "Characteristics of binderless palm biomass briquettes with various particle sizes." *Jurnal Teknologi* 77, no. 8 (2015). https://doi.org/10.11113/jt.v77.6147

[17] Kaliyan, Nalladurai, and R. Vance Morey. "Factors affecting strength and durability of densified biomass products." *Biomass and Bioenergy* 33, no. 3 (2009): 337-359. https://doi.org/10.1016/j.biombioe.2008.08.005

[18] Nasrin, A. B., A. N. Ma, Y. M. Choo, S. Mohamad, M. H. Rohaya, A. Azali, and Z. Zainal. "Oil palm biomass as potential substitution raw materials for commercial biomass briquettes production." *American Journal of Applied Sciences* 5, no. 3 (2008): 179-183. https://doi.org/10.3844/ajassp.2008.179.183

[19] Zannikos, F., S. Kalligeros, G. Anastopoulos, and E. Lois. "Converting biomass and waste plastic to solid fuel briquettes." *Journal of Renewable Energy* 2013 (2013). https://doi.org/10.1155/2013/360368

[20] Hanaffi Mohd Fuad, Muhammad Ariff, Hasan Mohd Faizal, Mohd Rosdzimin Abdul Rahman, and Z. A. Latiff. "Torrefaction of densified empty fruit bunches with addition of plastics waste." *Biofuels* (2018): 1-11. https://doi.org/10.1080/17597269.2018.1457312

[21] Faizal, Hasan Mohd, M. Shafiq M. Nazri, Md Mizanur Rahman, S. Syahrullail, and Z. A. Latiff. "Development of palm biomass briquettes with polyethylene plastic waste addition." *Jurnal Teknologi* 78, no. 9-2 (2016): 69-75. https://doi.org/10.11113/jt.v78.9657

[22] Garrido, Maria Angeles, Juan A. Conesa, and Maria Dolores Garcia. "Characterization and production of fuel briquettes made from biomass and plastic wastes." *Energies* 10, no. 7 (2017): 850. https://doi.org/10.3390/en10070850

[23] Bazargan, Alireza, Sarah L. Rough, and Gordon McKay. "Compaction of palm kernel shell biochars for application as solid fuel." *Biomass and Bioenergy* 70 (2014): 489-497. https://doi.org/10.1016/j.biombioe.2014.08.015

[24] Bazargan, Alireza, Sarah L. Rough, and Gordon McKay. "Fine tuning of process parameters for improving briquette production from palm kernel shell gasification waste." *Environmental Technology* 39, no. 7 (2017): 931-938. https://doi.org/10.1080/09593330.2017.1317835

[25] Si, Yaohui, Junhao Hu, Xianhua Wang, Haiping Yang, Yingquan Chen, Jingai Shao, and Hanping Chen. "Effect of carboxymethyl cellulose binder on the quality of biomass pellets." *Energy & Fuels* 30, no. 7 (2016): 5799-5808. https://doi.org/10.1021/acs.energyfuels.6b00869

[26] Nyakumaa, Bemgba Bevan, Arshad Ahmada, Anwar Joharia, Tuan Amran Tuan Abdullaha, and Olagoke Oladokuna. "Torrefaction of Pelletized Oil Palm Empty Fruit Bunches." In *The 21st International Symposium on Alcohol Fuels - 21st ISAF* (2015): 15-19.

[27] Peng, J. H., H. T. Bi, C. J. Lim, and S. Sokhansanj. "Study on density, hardness, and moisture uptake of torrefied wood pellets." *Energy & Fuels* 27, no. 2 (2013): 967-974. https://doi.org/10.1021/ef301928q

[28] Chen, Wei-Hsin, Yi-Qing Zhuang, Shih-Hsien Liu, Tarng-Tzuen Juang, and Chi-Ming Tsai. "Product characteristics from the torrefaction of oil palm fiber pellets in inert and oxidative atmospheres." *Bioresource Technology* 199 (2016): 367-374. https://doi.org/10.1016/j.biortech.2015.08.066

[29] Chen, Wei-Hsin, Jianghong Peng, and Xiaotao T. Bi. "A state-of-the-art review of biomass torrefaction, densification and applications." *Renewable and Sustainable Energy Reviews* 44 (2015): 847-866. https://doi.org/10.1016/j.rser.2014.12.039

[30] Yang, Zixu, Madhura Sarkar, Ajay Kumar, Jaya Shankar Tumuluru, and Raymond L. Huhnke. "Effects of torrefaction and densification on switchgrass pyrolysis products." *Bioresource Technology* 174 (2014): 266-273. https://doi.org/10.1016/j.biortech.2014.10.032

[31] Bergman, Patrick CA, A. R. Boersma, R. W. R. Zwart, and J. H. A. Kiel. "Torrefaction for biomass co-firing in existing coal-fired power stations." *Energy Research Centre of the Netherlands*, ECN-C-05-013 (2005).

[32] Prins, Mark J., Krzysztof J. Ptasinski, and Frans JJG Janssen. "Torrefaction of wood: Part 1. Weight loss kinetics." *Journal of Analytical and Applied Pyrolysis* 77, no. 1 (2006): 28-34. https://doi.org/10.1016/j.jaap.2006.01.002

[33] Li, Hui, Xinhua Liu, Robert Legros, Xiaotao T. Bi, C. Jim Lim, and Shahab Sokhansanj. "Pelletization of torrefied sawdust and properties of torrefied pellets." *Applied Energy* 93 (2012): 680-685. https://doi.org/10.1016/j.apenergy.2012.01.002

[34] Na, Byeong-Ill, Young-Hun Kim, Woo-Seok Lim, Soo-Min Lee, Hyoung-Woo Lee, and Jae-Won Lee. "Torrefaction of oil palm mesocarp fiber and their effect on pelletizing." *Biomass and Bioenergy* 52 (2013): 159-165. https://doi.org/10.1016/j.biombioe.2013.02.041

[35] Nyakuma, Bemgba B., Arshad Ahmad, Anwar Johari, Tuan Amran T. Abdullah, Olagoke Oladokun, Ali H. Al-Shatri, Adnan Ripin, and Afizah Alir. "Preliminary torrefaction of oil palm empty fruit bunch pellets." In *E3S Web of Conferences*, vol. 90, p. 01014. EDP Sciences, 2019. https://doi.org/10.1051/e3sconf/20199001014

[36] Faizal, Hasan Mohd, M. Amin M. Jusoh, Mohd Rosdzimin Abdul Rahman, S. Syahrullail, and Z. A. Latiff. "Torrefaction of palm biomass briquettes at different temperature." *Jurnal Teknologi* 78, no. 9-2 (2016): 61-67. https://doi.org/10.11113/jt.v78.9656

[37] Amini, Mohd Hazim Mohamad, Rokiah Hashim, Salim Hiziroglu, Nurul Syuhada Sulaiman, and Othman Sulaiman. "Properties of particleboard made from rubberwood using modified starch as binder." *Composites Part B: Engineering* 50 (2013): 259-264. https://doi.org/10.1016/j.compositesb.2013.02.020

[38] Yu, Wenbin, Hong He, Nanpu Cheng, Bingtai Gan, and Xuelian Li. "Preparation and experiments for a novel kind of foundry core binder made from modified potato starch." *Materials & Design* 30, no. 1 (2009): 210-213. https://doi.org/10.1016/j.matdes.2008.03.017

[39] Dhanalakshmi, K., and Suvendu Bhattacharya. "Compaction agglomeration of corn starch in presence of different binders." *Journal of Food Engineering* 104, no. 3 (2011): 348-355. https://doi.org/10.1016/j.jfoodeng.2010.12.027

[40] Law, H. C., L. M. Gan, and H. L. Gan. "Experimental Study on the Mechanical Properties of Biomass Briquettes from Different Agricultural Residues Combination." In *MATEC Web of Conferences*, vol. 225, p. 04026. EDP Sciences, 2018. https://doi.org/10.1051/matecconf/201822504026

[41] HRN, EN. "18134-2:2015 Solid biofuels-Determination of moisture content-Oven dry method-Part 2: Total moisture-Simplified method." *Croatian Standard Institute* (2015).

[42] ISO, EN. "18123:2015 Solid biofuels Determination of the content of volatile matter." *Norwegian Standards* (2015).

[43] ISO, EN. "18122:2015 Solid biofuels Determination of ash content." *Geneva, Switzerland* (2015).

[44] ISO, EN. "14918:2010 Solid Biofuels-Method for the determination of calorific value." *Swedish Standard* (2010).

[45] Rabier, Fabienne, Michaël Temmerman, Thorsten Böhm, Hans Hartmann, Peter Daugbjerg Jensen, Josef Rathbauer, Juan Carrasco, and Miguel Fernández. "Particle density determination of pellets and briquettes." *Biomass and Bioenergy* 30, no. 11 (2006): 954-963. https://doi.org/10.1016/j.biombioe.2006.06.006

[46] Bridgeman, T. G., J. M. Jones, I. Shield, and P. T. Williams. "Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties." *Fuel* 87, no. 6 (2008): 844-856. https://doi.org/10.1016/j.fuel.2007.05.041

[47] Huang, Yu-Fong, Pei-Hsin Cheng, Pei-Te Chiueh, and Shang-Lien Lo. "Leucaena biochar produced by microwave torrefaction: Fuel properties and energy efficiency." *Applied Energy* 204 (2017): 1018-1025. https://doi.org/10.1016/j.apenergy.2017.03.007

[48] ISO, EN. "18125:2017 Solid biofuels-Determination of calorific value." *International Organization for Standardization* (2017).

[49] Uemura, Yoshimitsu, Wissam N. Omar, Toshio Tsutsui, and Suzana Bt Yusup. "Torrefaction of oil palm wastes." *Fuel* 90, no. 8 (2011): 2585-2591. https://doi.org/10.1016/j.fuel.2011.03.021

[50] Noda, R., Y. Matsuhisa, T. Ito, and M. Horio. "Alkali metal evolution characteristics of wood biomass during pyrolysis and gasification." In *Proceedings for the Annual Meeting of the Japan Institute of Energy*, Japan, pp. 196-197. 2003.

[51] Susanty, W., and Z. Helwani. "Torrefaction of oil palm frond: The effect of process condition to calorific value and proximate analysis." In *IOP Conference Series: Materials Science and Engineering*, vol. 345, no. 1, p. 012016. IOP Publishing, 2018. https://doi.org/10.1088/1757-899X/345/1/012016

[52] Ahmad, R., K. Ismail, M. A. M. Ishak, N. N. Kasim, and C. Z. A. Abidin. "Pretreatment of palm kernel shell by torrefaction for co-gasification." In *4th IET Clean Energy and Technology Conference (CEAT 2016)*, pp. 1-6. IET, 2016. https://doi.org/10.1049/cp.2016.1327

[53] Asadullah, Mohammad, Ag Mohammad Adi, Nurul Suhada, Nur Hanina Malek, Muhammad Ilmam Saringat, and Amin Azdarpour. "Optimization of palm kernel shell torrefaction to produce energy densified bio-coal." *Energy Conversion and Management* 88 (2014): 1086-1093. https://doi.org/10.1016/j.enconman.2014.04.071