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TORREFIED FUEL PELLETS FROM SOLID WASTE OF SUGAR INDUSTRY

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Abstract

The preparation of fuel pellets from the filter cake waste from the sugar industry was studied. Pelletization by a hydraulic press at a pressure of 20 to 50 bar (2 to 5 MPa) was used to produce fuel pellets with a diameter of 1 cm and height of 1.25 cm. Energy efficiency of the resulting pellets was improved by thermal treatment called "torrefaction". During this process, the samples were heated to between 200 and 300°C for 0.5 to 2 h under a nitrogen atmosphere. The properties of fuel pellets including calorific value, bulk density, pellet density, proximate analysis, and compressive strength were characterized. The results demonstrated that the minimum pressure needed to produce the pellets without binder was 30 bar. The calorific value was between 13,954-14,468 kJ/kg for the resulting fuel pellet, which was significantly higher than that of the unpelletized raw material (11,197 kJ/kg). The fuel pellets had bulk density and pellet density of between 300-440 kg/m^3 and 720-890 kg/m^3, respectively. Increasing the time and temperature of torrefaction resulted in the lower yields of pellets. Fuel pellets maintain their shape and did not break under the applied torrefaction conditions. Torrefied pellets resulted in higher calorific value of 16,552-22,642 kJ/kg, higher carbon content, lower pellet and bulk densities compared to the fuel pellet without thermal treatment. The compressive strength of torrefied pellets decreased due to the delicate nature of the sample. The suggested conditions for optimal torrefied pellet in thermal and physical properties are 300°C and 1 h. The prepared fuel pellets showed comparable heating values to other fuels, and had properties in agreement with Thailand standards. Therefore, filter cake as a solid waste from production process of sugar has potential as raw material for the production of solid fuel pellets.

Keywords: **Pelletization, torrefication, solid waste, sugar industry**

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Introduction

Thailand is country with a significant focus towards agriculture, of which sugar production is one of the main industries. The sugar industry generates a variety of by-product such as bagasse, molasses and filter cake. Bagasse is used as fuel for electricity and steam generation. While obtained pulp can be used to produce paper, board and food packaging (plates and bowls) and can also be used to manufacture chemicals such as furfural (George, 2010). Molasses used to produce ethanol, monosodium glutamate, vinegar and as an animal feed. Filter cake used as a fertilizer or soil improver. The extracted wax from filter cake can be use in the production of polish, carbon paper ink, and lipstick. Due to the limitation direct use of filter cake, this work try to find new alternative way to increase the value of this by-product.

Filter cake is obtained at clarification process. It is spongy, dark or even back, and has high moisture content (George, 2010). This by-product consists of organic and inorganic components from bagasse, lime, mud, soil and sugar. The components of filter cake include cellulose 8.9%, hemicellulose 2.4%, lignin 1.2% and fat and wax 9.5% (George, 2010). The main element of filter cake is carbon (32.5%) which is the source of energy. The trace amounts of hydrogen (2.2%), nitrogen (2.2%) and phosphorous (2.4%) are also elements of filter cake (George, 2010). Due to lignocellulosic material and high carbon content, filter cake can be exploited as a solid fuel for renewable energy production.

For better handling, transportation and storage of fuel, densification processes have been applied (Zhai, 2018). The pelletization process results in higher density, increased energy and improved mechanical strength (Zhai, 2018). To make pellets with strong inter-particle bonding, a binder may be added. The most preferred binders during pelletization are molasses (Zhai, 2018), molasses/lime (Zhai, 2018), glycerin (Jamradloedluk and Lertsatitthanakorn, 2015; Xia *et al.* 2019), and paraffin (Xia *et al.* 2019). However, this work does not use a binder but applies pressure in order to form pellets.

Moreover, one potential treatment for pellets is torrefaction, which can improve quality of solid fuel, leading to higher calorific value, lower moisture content due to hydrophobicity, uniform properties, and easy of transportation (Sukiran *et al.*, 2017). The fixed carbon content of torrefied fuel is higher than the raw material and energy density can increased by ~30% (Pulka *et al.*, 2019). Torrefaction process is a mild thermal treatment at 200-300°C under atmospheric pressure in the absence of oxygen with heating rate below 50°C (Sulaiman *et al.*, 2016). This process also known as mild pyrolysis and is a pre-treatment process applicable to biomass in order to convert it into compatible energy fuels (Matali *et al.*, 2016). Torrefaction differs from pyrolysis, where the former's purpose is to retain solid mass yield, while enabling its energy content to be conserved and with incomplete removal of volatile matters (Matali *et al.*, 2016). During torrefaction, approximately 25-30% of mass reduction occurs (Asadullah *et al.*, 2014). However, as a result of torrefaction, sample exhibits brittle behavior and reduce mechanical strength. Even though the torrefaction process required energy consumption cost, the energy yield resulting from this process is approximately 80-90% (Chen 2015), decrease the handling and storage costs and reduce investment for co-firing application.

Torrefaction studies have previous focussed on woody biomass (Prins *et al.*, 2006; Arias *et al.*, 2008; Stelte *et al.*, 2011; Shang *et al.*, 2012; Tooyserkani *et al.*, 2013; Arteaga-Pérez *et al.*, 2015; Cao *et al.*, 2015; Matali *et al.*, 2016; Gaitán-Alvarez *et al.*, 2017; Mamvura *et al.*, 2018; Manouchehrinejad and Mani, 2018), agricultural byproducts such as oil palm (Uemura *et al.*, 2011; Asadullah *et al.*, 2014; Matali *et al.*, 2016; Sulaiman *et al.*, 2016; Faizal *et al.*, 2018), sugarcane bagasse (Manyuchi *et al.*, 2019), wheat straw (Stelte *et al.*, 2013; Azócar *et al.*, 2019), coconut leaves (Pestano and Jose, 2016) and marula seed (Mamvura *et al.*, 2018), and municipal waste such as sewadge sludge (Pulka *et al.*, 2019) and food waste (Samad *et al.*, 2017; Rahman *et al.*, 2019). However, torrefaction of filter cake waste from the sugar industry has not been reported in published literature.

Herein, this research aims to prepare solid fuel pellet from filter cake with no binder. The torrefaction behavior of solid fuel pellet is also studied. The effect of temperature and residence time is investigated. While the resulting fuel pellets are characterized for calorific value, bulk density, pellet density, proximate analysis, and compressive strength.

Materials and Methods

Material and sample preparation

Filter cake was collected from a sugar plant in Chaiyaphum, Thailand. The original material has high moisture content and irregular shape. The material was sun dried for 1 day and then oven dried at 110°C for 4 h. The resulting material was crushed by hammer mill and sieved to particle size 850 μm (mesh 20).

Pellet Preparation

Pelletization experiments were conducted by using hydraulic press (Figure 1(a)). A cylindrical mold 1 cm diameter with 1.25 cm high was used with a 25 hold (Figure 1(b)). The size of pellet is in accordance with the Thailand Standard for biomass pellets that specify the diameter and height of pellets to be 0.6-1.2 and 0.315-4 cm, respectively. For standard industrial use from EN 17225-6-Solid biofuels-Fuel specifications and classes-Part 6: Graded non-woody pellet indicate the diameter and height of pellets to be 0.6-2.5 and 0.315-4 cm for class A and 1.2-2.5 and 0.315-5 cm for class B, respectively (Azócar *et al*., 2019).

The dried and crushed filter cake was filled inside the mold and manually pressed at 20, 30, 40, and 50 bar. After pelletization with 20 and 30 bar, the height of pellet remained constant at 1.25 cm, but the height of pellet decreased at higher pressure of compression. To maintain a constant size of 1.25 cm, additional crushed filter cake was added to the mold.

Torrefaction Experiment

Fuel pellets were placed in an air tight metal reactor as shown in (Figure 2(a)) (diameter 5 cm, height 30 cm) with a gas in and outlet. The reactor was placed in an electrical furnace (Figure 2(b)) and heated up to the desired torrefaction temperature. The heating rate was 30°C min^{-1} and the nitrogen flow through the reactor was 100 $\text{cm}^3\ \text{min}^{-1}$. The residence time of the torrefaction process was started when the temperature reached the set point. Torrefaction was carried out at 200, 250, and 300°C with residence time of 0.5, 1, 1.5, and 2 h. The torrefied pellet yield (wt%) was determined by mass of pellet after torrefaction divided by mass of original pellet.

Characterization

A bomb calorimeter (GALLENKAMP) was used to determine the higher heating value (HHV), i.e. calorific value of the sample. The experiment was conducted under O_2 atmosphere to ensure complete combustion of the sample.

Bulk density is an important parameter for transportation. To find this parameter, samples were loaded into a 10×10×10 cm box. It was calculated by dividing the net weight of samples by volume of container. The reported bulk density values are the average of three repeat measurements.

Pellet density was determined by measuring the dimensions of sample using digital Vernier and its weight by using analytical balance with three decimal places. Pellet density was calculated by taking the ratio of weight to volume of pellet.

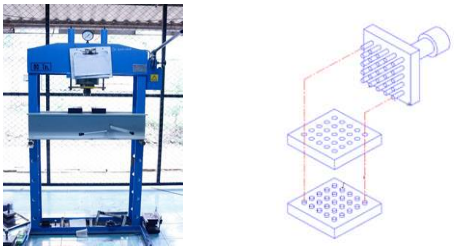
(a) (b)

Figure 1. Hydraulic press (a) and pelletization mold (b) used to densification of filter cake


(a) (b)

Figure 2. Reactor (a) and electrical furnace (b) used in torrefaction process

Proximate analysis includes moisture content, ash content, volatile matter and fixed carbon. Moisture content of sample was determined following the procedure given in EN 14774-1: 2009 Solid biofuels-Methods for determination of moisture content-Oven dry. 1 g of the sample was added to a crucible and oven dried at 105°C. The moisture content was determined by weight measurement in a 24 h interval and expressed in percent.

The sample was heated in a muffle furnace in order to determine ash content as stated in EN 14775: 2009 Solid biofuels-Methods for determination of ash content. Typically, the ash content was measured by weighting 1 g of sample, heated at 550°C for 1 h and expressed as a percentage.

Analysis of volatile matter was accomplished according to EN 15148: 2009 Solid biofuels. 1 g of sample was heated in a muffle furnace at 900°C for 7 min. Volatile matter is determined by measuring the weight loss, excluding weight of moisture. The fixed carbon in percentage was calculated by difference between 100 and sum of the volatile matter, moisture, and ash content.

Compressive strength or compressive resistance is the maximum crushing load a pellet can withstand before cracking or breaking. Compressive resistance test simulates the compressive stress due to weight of the top pellets on the lower pellets during storage in bins or silos and crushing of pellets in a screw conveyor (Kaliyan and Morey, 2009). Low hardness may also lead to breakage or damage of pellets during transportation and handling process, resulting in a reduction in efficiency for the pellet burner. It was measured axially and radially using the Universal Testing Machine (UTM) according to ASTM C 39-96.

Results and Discussion

Raw Material Analysis

The results of the proximate analysis, calorific value and bulk density of the filter cake after sun and oven dried are presented in Table 1. As received the filter cake has high moisture content (about 71.41 wt%) due to the sugar production process. After sun and oven drying, this material the moisture content of this material is significantly reduced (3.45 wt%). The fixed carbon content was 9.35 wt% and was comparable to other materials that are used as solid fuels such as mesocarp fibre of palm oil (9.4 wt%) (Faizal *et al*., 2018), *Dipterocarpus turbinatus* Gaertn wood sawdust (10.36 wt%) (Poddar *et al*., 2014), and Pongamia shell (11.86 wt%) (Prasad *et al*., 2015).

Table 1. Characteristics of filter cake

Proximate analysis (wt%)	
Moisture	3.45
Volatile matter	53.50
Fixed carbon	9.35
Ash	37.15
Calorific value (kJ/kg)	11,197
Bulk density (kg/m^3)	180

However, the ash content was significantly higher (37.15 wt%) due to the inorganic in filter cake. On a commercial scale, it should be a concern that the combustion of a material with high level of ash will require a more regular and effective ash removal process. Ash is abrasive and can cause corrosion of the metallic elements in the burners for long term use (Sette *et al*., 2018). Some materials that are used as fuels which also have high ash content include rice husks (21.84 wt%) (Purwanto *et al*., 2009), oil palm frond (Matali *et al*., 2016), and sewage sludge (43.10%) (Pulka *et al*., 2019).

The calorific value is a crucial indicator in the evaluation of solid fuel quality. The calorific value of the filter cake was 11,197 kJ/kg, and was comparable with other materials that used as fuel such as lignite or brown coal (5,250 kJ/kg) (Jones, 2010), rice straw (13,184 kJ/kg) (Purwanto *et al*., 2009), saw dust (13,425 kJ/kg) (Jamradloedluk and Lertsatitthanakorn, 2015), rice husk (13,435 kJ/kg) (Purwanto *et al*., 2009), and sewage sludge (13,503 kJ/kg) (Pulka *et al*., 2019).

The bulk density was 180 kg/m^3 which is consistent with other unprocessed forms of solid fuels, such as big bluestem (47 kg/m^3) (Theerarattananoon *et al*., 2011), wheat straw (48 kg/m^3) (Theerarattananoon *et al*., 2011), corn stover (51 kg/m^3) (Theerarattananoon *et al*., 2011), sorghum stalk (59 kg/m^3) (Theerarattananoon *et al*., 2011), Pongamia shell (146 kg/m^3) (Prasad *et al*., 2015), Douglas-fir wood (175 kg/m^3) (Tooyserkani *et al.* 2013), and *E. urophylla* wood (190 kg/m^3) (Sette *et al*., 2018). The pelletization process aids in increasing the bulk density of these solid fuels.

Fuel Pellet Analysis

Figure 3 shows fuel pellet products at various compression pressures. It was shown that not all pressures were suitable for pellet formation. The minimum compression pressure that can apply without binder was 30 bar. Therefore, the pellets from this condition were used in the heat treatment process.

As shown in Table 2, the densification of filter cake through pelletization, increases the calorific value in the order of 1.25-1.29 times (from 11,197 to 13,954-14,468 kJ/kg). These values are marginally lower than the Thailand Standard for biomass pellet (not less than 14,600 kJ/kg) and standard industrial use from EN 17225-6 (not less than 14,500 kJ/kg). However, the calorific value can be improved by heat treatment. In addition, calorific values of filter cake pellets were comparable to rice husks pellets

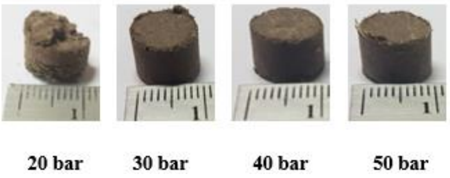

Figure 3. Fuel pellets from filter cake at various compressed pressure

Table 2. Properties of fuel pellets

Properties	30 bar	40 bar	50 bar
Calorific value (kJ/kg)	13,954	14,149	14,468
Bulk density (kg/m^3)	300	360	440
Pellet density (kg/m^3)	720	770	890
Proximate analysis (wt%)			
Moisture	2.95	3.37	3.64
Volatile matter	50.11	51.54	52.12
Fixed carbon	11.81	10.36	9.72
Ash	38.08	38.10	38.16
Compressive strength			
(kPa)	22.67	27.36	57.56
Axial	21.73	24.26	29.81
Radial			

(13,861-14,697 kJ/kg) (Ríos-Badrán *et al.*, 2020) and wheat straw pellet (15,430 kJ/kg) (Azócar *et al.*, 2019).

The results also showed that calorific value of pellets increased with increasing pelleting pressure. It was possible to pack more filter cake into the mold at elevated pressures, thus maintaining the height of pellet at 1.25 cm. This resulted in more sample within each pellet and a greater calorific value.

Pelletization of fuel significantly increases the bulk density value. The values of pellets ranged from 300 to 440 kg/m^3, approximately 1.67-2.44 times higher than the bulk density value before pelletization. This increase in fuel pellet bulk density can improve ease of handling (Theerarattananoon *et al.*, 2011). Increasing of pelletizing pressures resulted in an elevated bulk density of the fuel, as a result the additional filter cake added to the mold at high pressures to retain the consistent size of pellet. Therefore, the mass of each pellet increased with increasing pressure (and further addition of filter cake) while its shape remained constant. This consistent with the number of samples being load into the container but each increase in pressure lead to a greater resulting mass. Thus, the bulk density that is total mass of pellets divided by container volume is increased. Nevertheless, standard industrial use from EN 17225-6 specify bulk density of non-woody pellet as ≥600 kg/m^3 (Azócar *et al.*, 2019). The results of this property of filter cake pellets lower than the standard densities. However, other materials that used as fuel also had bulk density lower than the standard such as rice husks pellets (100 and 102 kg/m^3) (Ríos-Badrán *et al.*, 2020), wheat straw pellet (469 and 501 kg/m^3) (Zeng *et al.*, 2016; Azócar *et al.*, 2019), cocoa shell pellet (552 kg/m^3) (García *et al.*, 2019), Miscanthus (481 and 578.5 kg/m^3) (Kallis *et al.*, 2013; Zeng *et al.*, 2016), palm-oil residue pellet (580 kg/m^3) (Erlich and Fransson, 2011), grape pomace pellet (588 kg/m^3) (García *et al.*, 2019), and bagasse pellet (590 kg/m^3) (Erlich and Fransson, 2011).

Pellet density is a critical factor affecting the energy density, storage and transportation cost of fuel pellets (Cao *et al.*, 2015). Pellet density values are a factor affecting the energy density ranged from 720 to 890 kg/m^3. These values satisfied the Thailand Standard for biomass pellet (not less than 600 kg/m^3). The pellet densities of filter cake pellets were also comparable to other fuel such as sorghum stalk pellet (436-560 kg/m^3) (Theerarattananoon *et al.*, 2011), big bluestem pellet (517-778 kg/m^3) (Theerarattananoon *et al.*, 2011), corn stover pellet (529-843 kg/m^3) (Theerarattananoon *et al.*, 2011), wheat straw pellet (613-852 kg/m^3) (Theerarattananoon *et al.*, 2011), oil palm leaves pellet (906 kg/m^3) (Wattana *et al.*, 2017), and oil palm frond pellet (935 kg/m^3) (Wattana *et al.*, 2017). It is noticeable that pellet density was seen to increase with the increase of pelletizing pressure. As discussed previously, at high pressure additional filter cake was added to the mold to maintain the size of pellet. Therefore, the mass of each pellet increase while the volume remained constant.

The proximate analysis of fuel pellets is also presented in Table 2. The moisture content of the fuel pellets varied between 2.95 and 3.64 wt%, which in according with the value of Thailand Standard for biomass pellet (not more than 10 wt%) and standard industrial use from EN 17225-6 (not more than 12 and 15 wt% for class A and class B, respectively).

Nevertheless, according to the Thailand Standard for biomass pellet and standard industrial use from EN 17225-6 for class A and class B, the ash content should not higher than 20, 12, and 15 wt%, respectively. In this research, the ash content of filter cake pellets were approximately 38 wt%.

The compressive strength that observed in both axial and radial direction increased with pelletization pressure. The results clearly shown that the compressive strength in axial direction (22.67-57.56 kPa) higher than radial direction (21.73-29.81 kPa). This was due to the fact that our equipment compressed the sample in axial direction. Zhai *et al.* (2018) reported that increases in pellet density also resulted in high mechanical strength. The results of this study are in agreement of this statement when increasing the pelletizing pressure the pellet density also increased, as did the compressive strength in both axial and radial direction.

Torrefaction Results

Temperature and retention time are two main parameters that influence torrefaction process. Figure 4 shows fuel pellets after torrefication at various temperatures and times. The torrefied

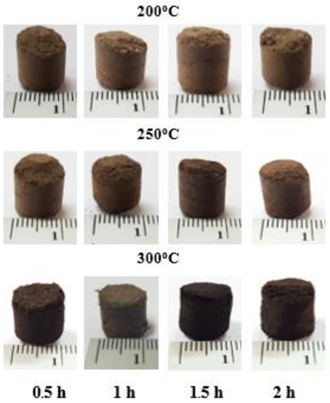

Figure 4. Torrefied fuel pellets (compression pressure 30 bar)

Table 3. Yield (wt%), calorific value, bulk density and pellet density of torrefied pellets

	0.5 h	1 h	1.5 h	2 h
200ºC				
Yield	96.58	96.10	95.18	94.74
Calorific value (kJ/kg)	16,552	16,697	16,723	16,809
Energy enhancement (%)	18.62	19.66	19.84	20.46
Bulk density (kg/m^3)	290	300	290	290
Pellet density (kg/m^3)	710	700	690	690
250ºC				
Yield	94.80	93.88	91.86	91.14
Calorific value (kJ/kg)	21,689	22,110	22,246	22,583
Energy enhancement (%)	55.43	58.45	59.42	61.84
Bulk density (kg/m^3)	280	280	270	280
Pellet density (kg/m^3)	710	690	690	670
300ºC				
Yield	67.02	59.20	57.39	54.18
Calorific value (kJ/kg)	22,338	22,351	22,421	22,642
Energy enhancement (%)	60.08	60.18	60.68	62.26
Bulk density (kg/m^3)	170	170	170	180
Pellet density (kg/m^3)	520	510	510	490

pellets at 300°C were moderately darker compared with lower torrefaction temperatures. The pellets still retained their shape and did not break, for all torrefaction temperatures and times.

Based on Table 3, the mass loss of fuel pellets slightly decreased at torrefaction temperature of 200 and 250°C, yield the torrefied pellets was around 91-97%. The very high mass loss or low yield occured at a torrefaction temperature of 300°C. This is due to the removal of water and volatile matter during torrefaction process at this temperature. The results of this research are in agreement with Pulka *et al.* (2019) who reported that mass lost during torrefaction of sewage sludge increased with higher torrefaction temperatures from 200 to 300°C. These results are also consistent with the observations reported in previous studies (Asadullah *et al.*, 2014; Matali *et al.*, 2016; Pestano and Jose, 2016; Samad *et al.*, 2017; Azócar *et al.*, 2019; Rahman *et al.*, 2019). Similarly, in the work of Matali *et al.* (2016) influence of temperature was more apparent for temperature range above 250°C when torrefied oil palm frond and woody biomass.

The drop in mass yield was greater for longer residence times, due to increased degradation that took place during the torrefaction process. Previously results reported that increased residence time also decreased the mass yield (Asadullah *et al.*, 2014; Pestano and Jose, 2016; Sulaiman *et al.*, 2016; Azócar *et al.*, 2019; Rahman *et al.*, 2019).

The calorific value of torrefied pellets increased from 13,954 kJ/kg to 16,552–22,642 (18.62-62.26%), when the torrefaction temperature and times were increased from 200 to 300°C and 0.5-2 h, respectively. This was due to the release of water as well as volatile compounds during torrefaction process resulting in increasing densification of carbon in product (see proximate analysis results in Table 4). In brief, an increase of the calorific value was due to the enrichment of carbon content of torrefied pellets. According to Mamvura *et al.* (2018), C=C, C-C, and C-H bonds contain higher energy compare to O-H bonds. This work demonstrated that an increase in the carbon content of the torrefied fuel resulting in higher calorific values. The increasing trend of higher calorific value with torrefaction temperature and time were consistent with the previous works (Asadullah *et al.*, 2014; Pestano and Jose, 2016; Matali *et al.*, 2016; Sulaiman *et al.*, 2016; Samad *et al.*, 2017; Azócar *et al.*, 2019; Rahman *et al.*, 2019). It has been reported that the calorific value of torrefied filter cake pellets were exceed the Thailand Standard for biomass pellet (not less than 14,600 kJ/kg) and standard industrial use from EN 17225-6 (not less than 14,500 kJ/kg).

The bulk density of torrefied pellets for all residence time did not significant decrease at 200 and 250°C (Table 3). However, for all residence time, the value decreased from 300 to 170-180 kg/m^3 at a torrefaction temperature of 300ºC. This was due to the highest mass lost at this temperature, however pellets retained their initial shape.

As shown in Table 3, torrefaction at 200 and 250°C did not affect the pellet densities for all residence times. On the other hand, the pellet densities significantly decreased from 720 to 490-520 kg/m^3 for torrefied pellets at 300ºC. The mass loss during torrefaction with constant cylindrical volume (shape did not shrink) was considered as the

Table 4. Proximate analysis and compressive strength of pellets torrefied at 300ºC for 0.5 and 1 h

	0.5 h	1 h
Proximate analysis (wt%)		
Moisture	1.05	1.03
Volatile matter	39.09	38.62
Fixed carbon	21.53	22.49
Ash	39.33	38.89
Compressive strength (kPa)		
Axial	18.65	16.19
Radial	16.26	13.20

Table 5. Comparison of calorific value of torrefied pellets obtained in this study with literatures

Raw material	Torrefaction		Calorific Value (kJ/kg)	Reference
	Temperature (°C)	Time (h)		
Filter cake (sugar plant)	200-300	0.5-2	16,552-22,642	This work
Wheat straw	145	50 min	16,010	(Azócar *et al*., 2019)
Cedarwood	240-300	0.5	19,870-23,170	(Cao *et al*., 2015)
Camphorwood	240-300	0.5	18,900-22,350	(Cao *et al*., 2015)
Scots pine	230-270	1	20,420-24,340	(Shang *et al*., 2012)

reason for lower densities of pellets. It was noted that torrefied pellets obtained at 300°C had pellet densities less than Thailand Standard for biomass pellet (less than 600 kg/m^3).

The torrefied pellet at 300°C had highest calorific value, however, the samples torrefied with residence time 1.5 and 2 h were easily broken into smaller particles due to more brittle when using higher torrefaction time and longer time. Thus, the proximate analysis and compressive strength were only conducted on torrefied pellets with residence time 0.5 and 1 h. In Table 4, the contents of volatile matter were reduced after torrefaction, whereas higher fixed carbon contents were observed. It was claimed that fixed carbon releases higher energy compared to volatile matter. Moreover, fixed carbon can burn steadily whereas volatile matter has higher thermal reactivity (Cao *et al*., 2015). However, a small increase in ash content was observed. In the untreated pellets, the moisture content was 2.95 wt%, which decreased on torrefaction, indicating that the torrefied pellets were characterized by hydrophobicity. Pulka *et al.* (2019) also indicated that moisture content and volatile matters decreased after torrefaction of sewage sludge at temperature of 200 to 300°C, but ash content increased. Matali *et al.* (2016) also showed a similar increasing trend of fixed carbon and decreasing trend of volatile matters with increasing torrefaction temperature of 200 to 300°C for torrefied fuel of oil palm frond. The fixed carbon, volatile matters, ash and moisture content trends were also similar to previous reported results (Pestano and Jose, 2016; Samad *et al*., 2017; Azócar *et al*., 2019; Rahman *et al*., 2019).

Decreasing compressive strength was observed for all pellets subjected to torrefaction, as shown in Table 4. Furthermore, the compressive strength of the pellets both in axial and radial direction decreased with the increasing of torrefaction time. The compressive strength decreased from 22.67 and 21.73 kPa (untreated pellets) to 16.19-18.65 and 13.20-16.26 kPa for axially and radially, respectively. This may be due to the sample becoming increasingly brittle after torrefaction.

Table 5 shows the comparison of calorific value of torrefied pellets obtained from filter cake with torrefied pellets prepared from other biomass sources. Based on the table, it can be said that the performance of the torrefied filter cake pellets produced in this present work are very competitive when compared with wheat straw (Azócar *et al*., 2019), cedarwood (Cao *et al*., 2015), camphorwood (Cao *et al*., 2015), and scots pine (Shang *et al*., 2012).

Conclusions

In conclusion, filter cake is a suitable solid waste for low pressure densification without binder to produce pellets for use as an alternative fuel. The pellets presented adequate characteristics including low moisture content (below 3.64%) and high calorific value (13,954-14,468 kJ/kg). The pelletization process resulted in a significant increase in bulk density from 180 to 300-440 kg/m^3. The uniform size of pellets, combined with high bulk density makes them easier handle, transport and store.

The torrefaction of pellet is a potential way to produce pellets with higher calorific values (16,552–22,642 kJ/kg). However, the mass yield also decreased, while the hydrophobicity of torrefied pellets resulting in lower moisture content (1.03-1.15%). Torrefaction also resulted in lower compression strength of the pellets from 22.67 to 15.36 kPa in axial direction and from 21.73 to 12.80 kPa in radial direction.

Further work will focus on developing applications for the residual ash post combustion of fuel pellets.

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