Characterization of torrefied biomass pellets from corncobs and rice husks for solid fuel production

N. Homdoung[1*], J. Uttaruan[1], K. Sasujit[1], T. Wongsiriumnauy[2], N. Tippayawong[3*]

(1. School of Renewable Energy, Maejo University, Chiang Mai 50290, Thailand;
2. Faculty of Engineering and Agro-industry, Maejo U niversity, Chiang Mai 50290, Thailand;
3. Department of Mechanical Engineering, Chiang Mai University, Chiang Mai 50200, Thailand)

Abstract: The aim of this research was to evaluate the changes in physico-chemical properties of agricultural residues (corn-cobs and rice husks) during torrefaction. Physical properties of the torrefied biomass pellets were analysed. The results showed that increasing the torrefaction temperature and time resulted in reduced moisture and volatile matter content of corn-cobs and rice husks. At the same time, fixed carbon, ash content and heating values were increased. The heating values of both torrefied fuels were in the range of 14.9–16.9 MJ kg^{-1}, increased by about 16% to 21% from the raw biomass. The optimum treatment conditions were found to be in the range 200°C–250°C and 20 min. Physical properties of both torrefied pellet fuels were found to be enhanced, and closer to those required by the associated standard. The average bulk density and durability of torrefied pellets were between 1112 and 1226 kg m^{-3} and 91% and 94%, respectively. The water resistance and compressive strength were in the range 89%–92% and 140–156 kg m^{-3}, respectively. The energy densities of corn-cob and rice husk torrefiled fuels were increased by 20.8% and 15.8% with compared to their original biomass inputs.

Keywords: agricultural residues, torrefaction, densification, torrefied biomass, solid fuels

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1 Introduction

At present, the supply of fossil fuel is declining, and the price is likely going to rise due to the increasing consumption of electricity. Thailand has been an oil importing country. Fortunately, Thailand is also an agricultural country with huge biomass resources. Development of alternative fuels from biomass should be encouraged. Previously, biomass energy consumption was inefficient due to lack of knowledge, technology and research support. Biomass materials from agricultural residues are normally eliminated by burning, causing a lot of problems, such as air pollution affecting the environment, human health, tourism and overall economics (Tippayawong et al., 2006). There are many biomass conversion methods (Jaroenkhasemmeesuk and Tippayawong, 2015; Punnarapong et al., 2017). Upgrading

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***Corresponding author: N. Homdoung,** Asst.Prof., School of Renewable Energy, Maejo University, Chiang Mai 50290, Thailand. Tel: +6653878590. Email: nigranghd@gmail.com.

N. Tippayawong, Prof., Department of Mechanical Engineering, Chiang Mai University, Chiang Mai 50200, Thailand. Tel:+6653944146. Email: n.tippayawong@yahoo.com.

biomass fuels by torrefaction and densification is an attractive approach whose energy can be used to replace fossil fuels and also helps to reduce the burning of waste materials by farmers. Torrefaction and densification increase the energy density and two technologies combined is called torrefied pellet fuels. The transportation, storage and management of upgraded solid fuels are expected to be simpler. They can be widely used in the production of heat or power generation. That reduces sulfur dioxide (SO_2) and carbon dioxide (CO_2) emissions into the atmosphere. Torrefaction is a mild pyrolysis process that decreases the moisture content of solid biomass and transforms it into a brittle, char-type material called torrefied fuels (Safin et al., 2017). Normally, the heating value of torrefied fuels gradually increases from 19 MJ kg^{-1} to 21 or 23 MJ kg^{-1} for torrefied wood (Mamvura et al., 2018). The torrefaction process can reduce the initial mass by 20%–30%. During torrefaction, the solid biomass was heated in the absence of oxygen in the range of 200℃–400°C leading to a loss of moisture and partial loss of the volatile matter (Rattanaphaiboon et al., 2017). The characteristics of the biomass were considerably changed. The tenacious fibre structure of the original biomass material was largely destroyed through the breakdown of hemicellulose and to a lesser degree of cellulose molecules, so that the material became brittle and easy to grind (Mamvura et al., 2018).

Torrefied fuels can be used to replace or partially substitute coal without major rework of the existing fuel systems such as steam power plants, steel plants, combustion units and gasifiers (Thrän et al., 2016; Kuzmina et al., 2016; Mandova et al., 2018; Barskov et al., 2019). More importantly, the approach helps reduce greenhouse gas emissions (Bałazińska, 2017). The optimum torrefaction temperature depends on the type of biomass or proportions of hemicellulose cellulose and lignin (Mamvura et al., 2018; Chen et al., 2018). The use of torrefaction temperature and time in a range of 220℃-280°C and 30-120 min resulted in high heating value of torrefied fuels such as orange and grapefruit peel, rice straw, wood and sewage sludge (Tamelova et al., 2018; Kizuka et al., 2019; Urbancl et al., 2019). The torrefaction temperature and time were related to decreasing moisture, volatile while increasing fixed carbon and ash content. The fixed carbon affected the heating value of torrefied fuels (Homdoung et al., 2019). The torrefied fuels offer an alternative way for operation in various industries (Ribeiro et al., 2018).

Biomass densification is the process of increasing the density of biomass, which is also known as compaction. Densification involves applying pressure to mechanically densify the material. Generally, densification technology has many types such as briquettes, pellets, bales, cubes and pucks (Sokhansanj and Turhollow, 2004; Hamid et al., 2016). Pelletization process offers high in density and is easier to handle than other densified biomass products (Ribeiro et al., 2018). Pellet fuel is useful for supporting agriculture, communities and industry to turn into energy which can be completely utilized (Kažimírová et al., 2017; Brunerová et al., 2017, 2018). However, biomass pellet fuel production is high energy consumption, and leading to high price (Abdoli et al., 2018). In Philippines, the cost of biomass pellet fuel production was about USD 88–92 tonne^{-1}, while in the European countries, an average cost was in a range of EUR 118-150 tonne^{-1} at 10,000 (t/y) of annual pellet production (Jara et al., 2016; Nunes et al., 2014).

Biomass pelletizing machines are classified into two groups, consisting of ring die press and disc die press that work on pressing grinded biomass through a perforated die with compression of rotating cylindrical rollers (Güneş and Çelik, 2017). In general, the biomass pellet standard of bulk density, diameter and length are defined as having ⩾s600 kg m^{-3}, 6-12 mm and 3.15-40 mm, respectively (Rollinson and Williams, 2016), while the heating value can be used in minimum value with referring to EN14961-1. For low calorific value biomass, the calorific value can be increased by mixing techniques and producing biomass pellets with a lower diameter (Ríos-Badrán et al., 2020;

Iftikhar et al., 2019; Križan et al., 2018). The specification of biomass pellet with blends and mixtures can be checked from EN14961-6.

In addition, the biomass pellet durability, water resistance, compressive strength or other physical properties are essential for safe storage, implementation, transportation or increasing the standard requirements in the future (Williams et al., 2018; Gaitán-Alvarez et al., 2017). Development and research on biomass quality enhancements are essential to the use of biomass in the industrial sector or other energy uses. Therefore, this research presents an assessment of torrefied biomass pellets properties from agricultural residues available in Thailand. The effect of torrefaction parameters were considered on mass and energy yields, energy content, physical properties and energy balance. This study will increase the biomass energy efficiency and the economic value of agricultural residues in Southeast Asia.

2 Methodology

2.1 Biomass preparation

The agricultural residues used were corn-cobs and rice husks from Northern Thailand, shown in Figure 1. Corn-cobs were obtained from corn milling in farms. In general, 24% was corn-cobs and 62% of the remaining was grains, straw and other parts. Rice husks were obtained from a local rice mill. On average, remaining rice husk in farms is about 240 kg/acre in Northern Thailand. The moisture content of both biomass materials was 8%–9%, while the heating value was between 12.87 and 13.99 MJ kg^{-1}. The details of proximate and ultimate analysis results of both biomasses are shown in Table 1. They were crushed to reduce the size, then a Tyler sieve number 16 was used to select an average size of 1 mm and stored.

Figure 1 Corncobs and rice husks used for experiments

Table 1 Properties of the corncob and rice husk samples

Proximate analysis (air dry basis)	Corn-cobs	Rice husks
Moisture, wt%	9.2	8.15
Volatile matter, wt%	71.82	59.19
Fixed carbon, wt%	13.2	14.32
Ash, wt%	5.79	18.34
High heating value (MJ kg^{-1})	16.16	14.61
bulk density (kg m^{-3})	132.6	102.1
Ultimate analysis (dry ash free basis)		
Carbon, wt%	49.55	49.37
Hydrogen, wt%	6.46	6.63
Nitrogen, wt%	0.53	0.50
Oxygen, wt%	43.44	43.49
Sulfur, wt%	0.01	0.00

2.2 Torrefaction experimental set-up

Two types of biomass were torrefied at different temperatures and times. The optimum condition for torrefaction temperature and time were determined based on the mass and energy yields. Suitable torrefaction temperature and time were used to produce torrefied pellet fuels with a high-capacity torrefaction reactor. Finally, the analysis of the physical properties of torrefied pellet fuels was conducted, shown in Figure 2. The torrefaction reactor was equipped with an electrical heater of 5.0 kW, capable of reaching a maximum temperature of 1500°C. The reactor temperature was controlled by cold water flow with a water pump and heat exchanger arrangement. The temperature measurement was done using a type K thermocouple and controlled with a semi-automatic electronic system, 220 V, single phase, 50 Hz. The carrier gas in the process was adjusted to 5 L h^{-1}. After the torrefaction process, the torrefied fuels were taken for proximate analysis to determine the moisture, volatile matter, fixed carbon and ash content following relevant standards (Omar et al., 2017). High heating values were determined from bomb calorimeter. The mass and energy yields were evaluated from mass and energy input and output in the process (Poudel and Oh, 2014). The high-capacity torrefaction reactor employed liquefied petroleum gas as fuel for heating the torrefaction process. The reactor was in a cylindrical shape with the gas burner installed to provide external heat. Nitrogen was used to flow in the process. The high-capacity torrefaction reactor was operated similarly to the laboratory scale set-up. The torrefied fuels produced were light brown and subsequently compressed into pellet form. The pelletizing machine used a power of 5 HP coupling with a gear reducer, flat die and roller wraps. The diameter of the hole flat die was 8 mm and the production rate was between 150 and 250 kg h^{-1} depending on the type of biomass.

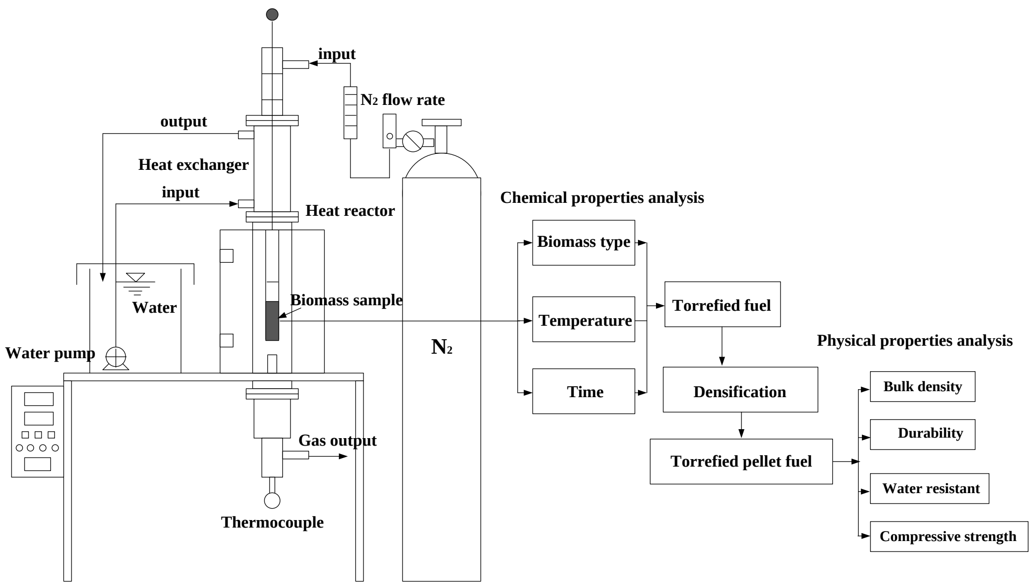


Figure 2 Schematic diagram of the torrefaction experiment for pellet fuels

2.3 Test conditions

Experiments were carried out to study the effect of three factors on the torrefaction process, namely the type of biomass, temperature and time. The torrefaction temperature was varied in a range of 200°C–400°C while torrefaction time was varied for 20, 40 and 60 min. Determination of physical properties of the torrefied pellet fuels, such as bulk density, durability, water resistance and compressive strength was performed (Peng et al., 2013).

3 Result and discussions

3.1 Effect of torrefaction temperature and residence time

Figure 3 shows the effect of torrefaction temperature on proximate composition of solid products at a residence time of 40 min. The moisture and volatile content of the torrefied fuels were found to decrease with the increasing torrefaction temperature, while the fixed carbon and ash were increased, similar to that reported in a previous study (Wongsiriamnuay and Tippayawong, 2012). At more than 100°C, some moisture was unable to evaporate from the biomass (Chen et al., 2016). The average remaining moisture in the torrefied fuel was about 3.9%–6.4%, depending on torrefaction time (Saeed et al., 2015). The reduced volatile matter was caused by decomposition of biomass components, such as extractive, hemicellulose, cellulose and lignin (Tumuluru, 2016). Decreasing volatiles led to reduced mass yield (Wilk and Magdziarz, 2017). Increasing torrefaction temperature increased fixed carbon percentage of the biomass. The fixed carbon content had an inverse relationship with the volatile matter. Because of the high volatile content in the chemical composition of the biomass, increasing heat treatment increased the fixed carbon content (Parikh et al., 2005). Increasing fixed carbon led to an increase in the heating value of the fuel (Özyuğuran and Yaman, 2017), hence, low fuel consumption in the combustion process. The fraction of ash content increased with the increasing torrefaction temperature because moisture and some volatile matter were released from the raw materials (Borges et al., 2016). Corn-cobs were shown to have higher moisture than rice husk, whereas the ash content of rice husk was higher than for corn-cobs. The moisture of both torrefied fuels was in a range of 0.25%–3%, while the volatile matter was between 32% and 70%.

Figure 4 shows the moisture, volatile matter, fixed carbon and ash content after the torrefaction process at varying residence times and fixed torrefaction temperature of 300°C. It was found that an increase in residence time led to the decreased moisture and volatiles of both biomasses (Li et al., 2015). The average reduction in the moisture of both biomasses was similar while the volatiles were different. The moisture content of both biomasses was on average decreased by about 65% while the volatile matter of corn-cobs and rice husks were reduced by 12% and 9%, respectively. However, the corn-cobs had higher moisture content than the rice husks. The fixed carbon and ash content were increased with the increasing residence time. The corn-cobs had higher fixed carbon than the rice husks, while the ash content was the opposite. Increasing residence time resulted in higher fixed carbon and ash, by more than 4 and 2 times, respectively.

3.2 Mass and energy yields

Mass yield is defined as the mass or weight ratio between torrefied biomass and raw biomass under various combinations of torrefaction temperature and time while the energy yield is defined as the useful energy from torrefaction compared with the energy of raw material (Bridgeman et al., 2008). Figure 5 shows the mass yields of corn-cobs and rice husk after torrefaction. Increasing the torrefaction temperature decreased mass yield due to the degradation of hemicellulose, cellulose and lignin. Some moisture or water was eliminated (Chiou et al., 2015). Consequently, the mass reduction led to increasing energy density (Medic et al., 2010). Increasing residence time decreased mass yield but that was quite low compared with the effect of an increase in torrefaction temperature. Reduction of mass yield was from the decomposition of three main polymeric structures (Sadaka and Negi, 2000). The yield of corn-cobs showed higher mass loss than rice husks, especially at torrefaction temperatures between 250 ℃ and 350°C for corn-cobs and 300°C–350°C for rice husks. This was due to the difference in chemical components (Wannapeera et al., 2008). In general, the hemicellulose was the most active and subjected to limited devolatilization and carbonization below 250°C. Cellulose decomposed at 305°C–375°C and lignin gradually did over the temperature range of 250°C–500°C (Mamvura et al., 2018). The energy yield was decreased with increasing torrefaction temperature, as shown in Figure 6. Adjusting the residence time had little effect on energy yield, except between 250°C and 350°C. The mass and energy yields were very important in choosing the torrefaction conditions. Therefore, the optimum conditions to produce torrefied fuels from corn-cobs and rice husks were obtained at 200°C and 250°C, respectively, with a fixed residence time of 20 min.

3.3 Energy content

Figure 7 shows the effect of torrefaction temperature and time on the high heating value of corn-cobs and rice husks. The energy value was increased with the increasing torrefaction temperature and time due to the reduction of moisture and some volatile matter (Nobre et al., 2015). Increasing fixed carbon led to an increase in the heating value of fuel (Hasan et al., 2017). However, the use of corn-cobs provided a higher heating value than rice husk with varying temperature and time. Higher energy content was related to chemical properties such as volatile matter, ash content, hemicellulose, cellulose, lignin and other extractives. The torrefaction temperature and time were important variables for changing biomass properties to increase the heating value. Maximum heating values of corn-cobs and rice husks at the highest torrefaction temperature were 23.7 and 15.8 MJ kg^{-1}, respectively. However, production of the torrefied fuel in this research was selected at 200°C and 250°C and 20 min. At this condition, the high heating values of the torrefied pellets were expected to be 16.9 and 14.9 MJ kg^{-1} for corn-cobs and rice husks, respectively.

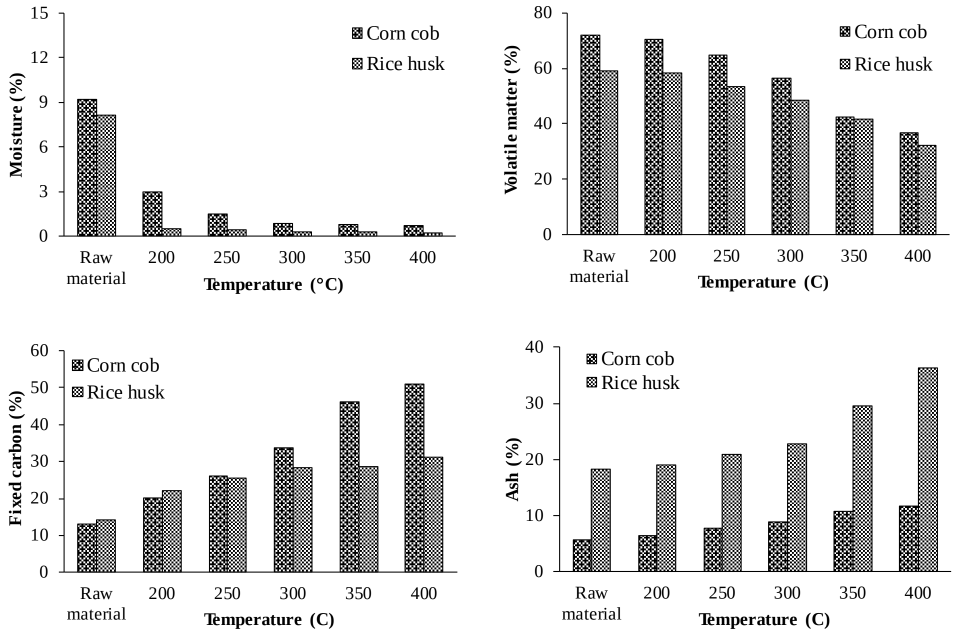


Figure 3 Effect of torrefaction temperature on proximate properties at 40 min of residence time

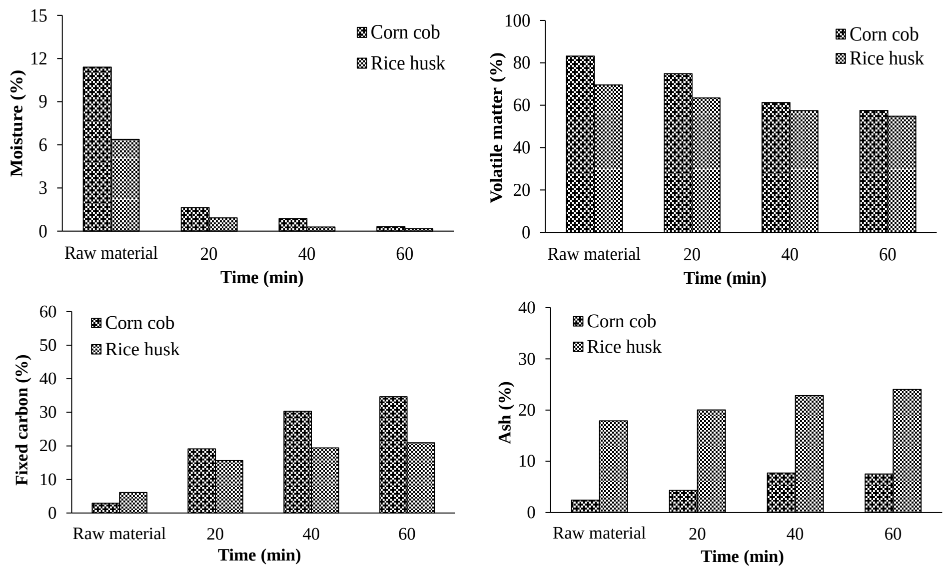


Figure 4 Effect of residence time on proximate properties at 300 °C of torrefaction temperature

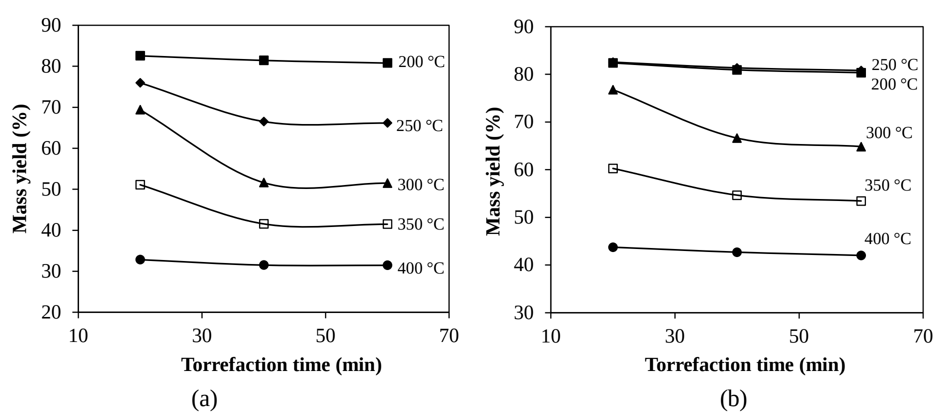
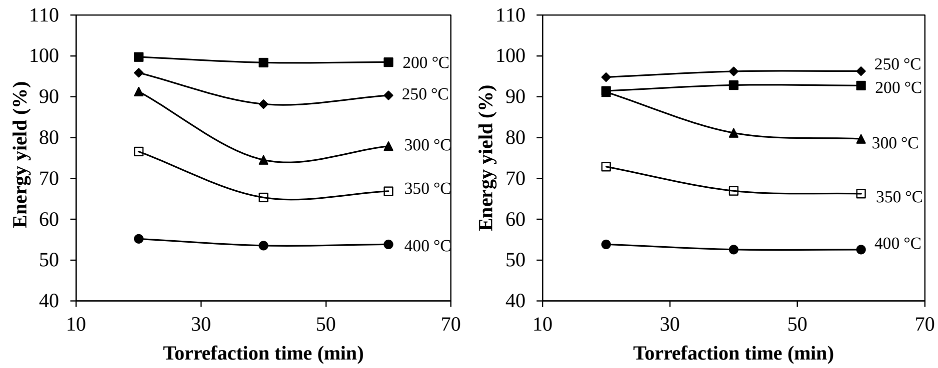


Figure 5 The mass yield of corncob (a) and rice husk (b)



(a) (b)

Figure 6 The energy yield of corncob (a) and rice husk (b)

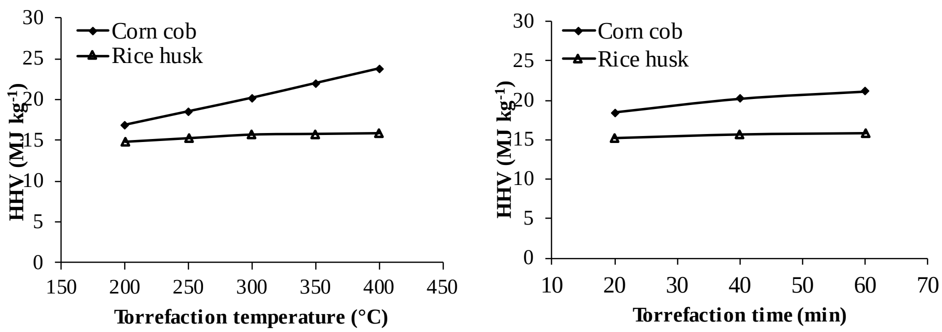


Figure 7 The effect of torrefaction temperature and time on heating value

3.4 Physical properties of torrefied pellet fuels

Figure 8 shows the bulk density and durability of the torrefied pellet fuels using corn-cobs and rice husks after torrefaction. In this experiment, a binder was not used with palletization. High-temperature conditions and the use of volatile compounds in self-synchronization was adapted (Shoaib et al., 2013). It was found that the bulk density of all torrefied pellet fuels was similar. However, the raw pellet fuels had higher bulk density than the torrefied pellet fuel due to the reduction in volatile matter (Nobre et al., 2015). The torrefied pellet fuels from corn-cobs had higher bulk density than those from rice husks. The main reason was associated with a higher fraction of volatile matter in the polymer structure. The bulk density of torrefied pellet fuels obtained was in a range of 1112–1226 kg m^{-3}, while the raw pellet fuels were between 1129 and 1246 kg m^{-3}, Nevertheless, when compared with the standard pellets, all pellets had a bulk density greater than 50% (Tippayawong et al, 2019). The durability of all pellet fuels was found to be in the range of 90.6%–93.6%, higher than standard pellets. The torrefied pellet fuels had durability slightly lower than raw pellet fuels, by less than 1.7%–2%. Reduction in the durability of the torrefied pellet fuels occurred when the inner space of pelletized fuel was increased, caused by evaporation of water and release of volatile matter. When subjected to a machine test at 50 cycle min^{-1}, the torrefied pellet fuels were easier to break down than the raw pellet fuels. Normally, the standard pellets fuels are expected to have a durability of 90% or more. Figure 9 shows the water resistance and compressive strength of the torrefied pellet fuels, compared with the raw pellet fuels. The torrefied pellet fuels showed slightly higher water resistance than the raw pellet fuels, while the use of rice husk had higher water resistance than corn-cobs. This was because of the high porosity and gap of corn-cobs compared with rice husks (Muazu and Stegemann, 2013). At the same time, the use of torrefied fuels to produce pellets led to increased coating with some volatile matter and reduced speed of water through the torrefied pellet fuels. Maximum water resistance of both torrefied pellet fuels was in the range of 88.7%–91.9%, while water resistance of both raw pellet fuels was between 85.6% and

91.5%. Thus, the use of corn-cob pellets may require a binder to meet the water resistance requirement. The compressive strength of all pellet fuels obtained was similar, between 140 and 156 kg m^{-3}. The torrefied pellet fuels showed slightly lower compressive strength than the raw pellet fuels, by less than 5.3%. Corn-cobs appeared to show higher compressive strength than rice husks. Reduction in compressive strength was due to the degradation of hemicelluloses and some celluloses in torrefaction (Stelte et al., 2011). Bonding and failure mechanisms in the torrefied pellet fuels may be studied further by means of fracture surface analysis using scanning electron microscopy (Ramos-Carmona et al., 2017).

3.5 Energy balance of the torrefaction process

Figure 10 shows the energy balance diagrams of the torrefaction proceses for corn-cobs and rice husks. The initial heating values of both raw materials were 13.9 and 12.87 MJ kg^{-1}, respectively, while moisture content was less than 11% in as-received basis. The mass losses occurred for corn-cobs and rice husks were 21.1% and 34.9%, respectively. The rice husk showed higher mass loss because it used higher torrefaction temperature (Stelte et al., 2011). The energy contents of the corn-cob and rice husk torrefiled fuels obtained were 13.31 and 9.96 MJ, respectively. The energy contents of the volatile release from both biomass materials after torrefaction were 1.03 and 1.68 MJ, respectively. However, the energy released can be used as auxiliary heat to preheat biomass before entering the torrefaction or being burned in the torrefaction reactor. This way, the energy efficiency of the system was improved (Granados et al., 2014). The energy densities of corncob and rice husk torrefiled fuels were 16.9 and 14.9 MJ kg^{-1}, increased by 20.8% and 15.8%, respectively, when compared to their original biomass inputs. The findings here were in similar magnitude to those reported by other researchers (Granados et al., 2014; Aytenew et al., 2018).

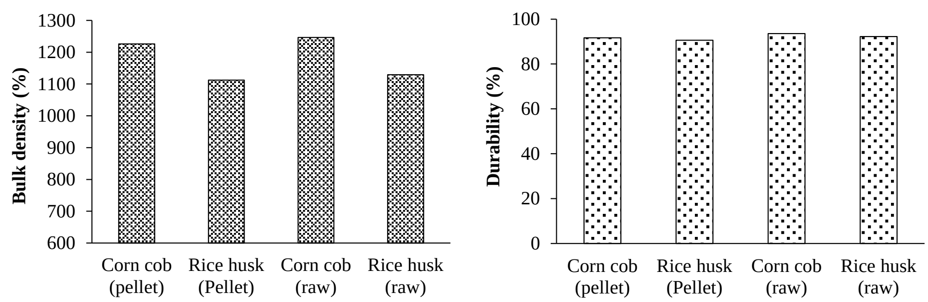


Figure 8 The bulk density and durability of torrefied and raw pellet fuels

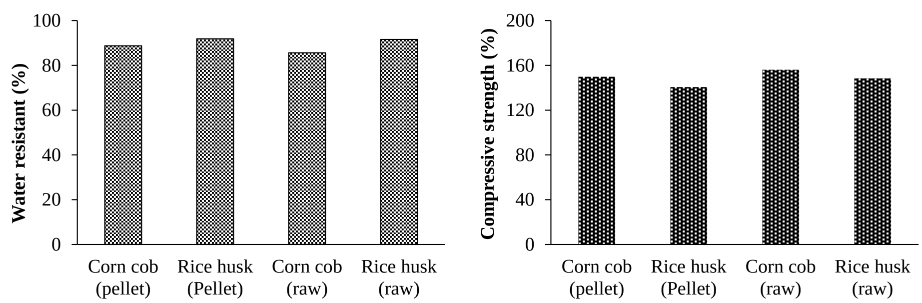


Figure 9 Water resistance and compressive strength of torrefied and raw pellet fuels

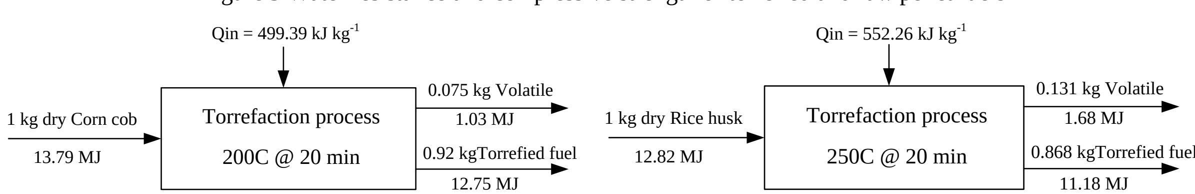


Figure 10 Energy balance diagrams

4 Conclusion

The experimental results can be summarized as follows; Corncobs and rice husks were technically feasible for the production of torrefied pellet fuels. In this work, the percentage of moisture and volatiles tended to decrease in the torrefaction process, while the fixed carbon and ash content were increased with increasing torrefaction temperature and time.

The optimum torrefaction conditions of corncobs and rice husks were obtained in a range of 200℃–250°C and 20 min. The heating values of the torrefied pellet fuels were increased by 20.8% and 15.8%, to 16.9 and 14.9 MJ kg^{-1}, respectively.

Most physical properties of the torrefied pellet fuels complied with the pellet fuel standards. The average bulk density and durability of the torrefied pellet fuels were in the range of 1112–1226 kg m^{-3} and 90.6%–93.6%, respectively. The water resistance and compressive strength were in the range of 88.7%–91.9% and 140–156 kg m^{-3}.

The torrefied pellet fuels from corncobs and rice husks had the potential to be used as a substitute for fossil fuels in thermal power plants, combustion units and electricity generation. However, there should be a further study on industrial production and commercialization.

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