

EFFECTS OF TORREFACTION TEMPERATURE AND RESIDENCE TIME ON AGRICULTURAL RESIDUE AFTER PELLETTIZATION PROCESS: CORNCOBS/ CORNHUSKS, RICE STRAW, AND SUGARCANE TRASH

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Abstract

Agricultural residues have a low bulk density, which requires larger storage space and higher transport costs compared with wood and other types of fuels. However, agricultural residues could be utilized as solid fuel by transforming them into biomass pellets, which would increase their bulk density. Furthermore, technology such as the torrefaction process could be applied in order to enhance the heating values of the biomass pellets. The effects of the torrefaction temperature and residence time (RT) on the moisture content (MC), density, volatile matter (VM), ash, fixed carbon (FC), heating value, mass yield (MY), and energy yield (EY) of selected agricultural residues, comprising corncobs/ cornhusks, rice straw, and sugarcane trash, after pelletization were studied. The MC of all the torrefied pellets was lower than 2%wt (wet basis), while the ash, FC, and heating value tended to increase with the increase of the temperature and RT for all types of residues. The density, VM, MY, and EY tended to decrease, probably because of the exothermic reaction occurrence, resulting in hemicellulose decomposition into a char-like solid product and volatiles, which oxygenated and hydrogenated the compounds. In conclusion, pelletization before torrefaction could be considered as the most appropriate approach for further development because a low temperature and short processing time are required, there is a reduced area for storage after production, and the quality of the product is high.

Keywords: Torrefaction, biomass, corncobs, cornhusks, pellets, rice straw, sugarcane trash

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Introduction

Worldwide, agricultural residues have been used as bedding, feed for cattle, fertilizer, and as a biomass fuel. Agricultural residues are less often used for biomass fuel because they have a lower bulk density and higher transport costs than other fuels. However, the bulk density of agricultural residues can be increased through being compacted into forms such as briquettes, bales, cubes, pucks, chips, and pellets. Moreover, the application of biomass pellets on a large-scale is through co-firing as a partial substitute for coal (Verhoest and Ryckmans, 2014). Thus, agricultural residues are better when they are pelletized before utilization. Pelletization of agricultural residues is an interesting option to improve the properties of agricultural residues for the generation of heat and power (Van der Stelt *et al.*, 2011). The advantages of biomass pellets are ease of use, storage, transport, process, and reduced environmental impact. On the other hand, the biomass pellets are not durable in the presence of elevated humidity. Mechanical strength and water uptake tests show that the durability of torrefied pellets is higher than that of conventionally produced biomass pellets (Bergman, 2005).

Torrefaction, a process different from carbonization, is a mild pyrolysis process carried out in a temperature range of 200-

300°C in the absence of oxygen (Busu, 2010). Potential products from the torrefaction process are char (torrefied), tar, and gas (Lu and Chen, 2014). The advantages of torrefication are low moisture content and increased heating values (Pach *et al.*, 2002; Prabir, 2010), an increase in the oxygen-to-carbon (O/C) ratio that improves its gasification efficiency, reduced power requirement for size reduction, improved handling, and a cleaner-burning fuel with little acid in the smoke. Hence, agricultural residues have been upgraded to high quality with a lower moisture content, higher density, and higher heating values using pelletization and torrefaction. In reviewing the literature concerning torrefaction, for the product yields and characteristics of corncob waste torrefied at temperatures of 250°C and 300°C, the results suggest that a higher torrefaction temperature makes the properties of the solid products approach those of coal. However, the solid yield and the energy yield decrease as the torrefaction temperature rises (Lu and Chen, 2014).

In general, wood and agricultural residues undergo torrefaction before pelletization. This process is, however, unsuitable for use in steeply cultivated fields because locations such as these require the pelletization to be conducted in the field for increased density and ease of transportation to facilities where torrefaction can be performed on the pellets later.



Figure 1. Photographs of agricultural residue



Figure 2. Photographs of agricultural residue pellets or biomass pellets



Figure 3. Photograph of the torrefaction chamber

However, previous studies have not reported on the effects of torrefaction of agricultural residues after pelletization. Therefore, the objective of this study was to observe the effects of RT and temperature during torrefaction of biomass pellets derived from corncobs/cornhusks, rice straw, and sugarcane trash on their fuel properties, mass yields, and energy yields. The results of this study provide essential knowledge for further improvement of agricultural residue into high-quality biomass fuel.

Materials and Method

Biomass Materials

Corncoobs/cornhusks, rice straw, and sugarcane trash (Figure 1) were respectively obtained from Chiang Mai, Nakhon Ratchasima, and Suphanburi provinces, Thailand. The agricultural residues were pelletized into a cylindrical shape (Figure 2) with a diameter of 8 mm and a length ranging from 20 to 45 mm using a pellet mill. The average bulk density was 579 kg/m³ for corncoobs/cornhusks, 598 kg/m³ for rice straw, and 717 kg/m³ for sugarcane trash (Table 1).

Experimental Apparatus and Procedure

The torrefaction chamber (Figure 3) is a fixed bed heated by a 3.08 kW heater element

which provides a maximum temperature of 1100°C. The torrefaction chamber consists of a tube (stainless steel 253MA) 50 mm in diameter and with a height of 620 mm, which has a sieve cylinder to contain the sample and ceramic fiber insulators on the outside. The system in our study was controlled by 8 programs, which provided a temperature control to a maximum temperature of 1100°C and a maximum heating rate of 100°C/min. Two k-type thermocouples were used, one for measuring the temperature outside the chamber and the other for monitoring the sample temperature inside the torrefaction chamber. Simultaneously, nitrogen was supplied into the chamber by a flow meter which measured the flow rate of the nitrogen as it was supplied to the torrefaction chamber (Figure 4).

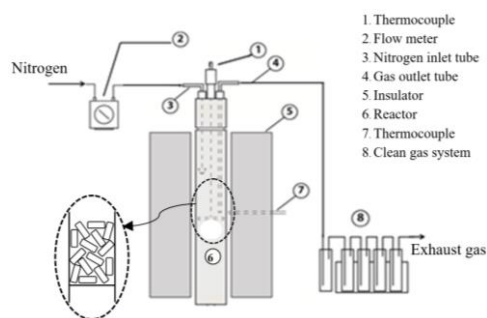


Figure 4. Schematic of the torrefaction system

Table 1. Properties of agricultural residue

Properties	Pellets		
	Corncoobs/ cornhusks	Rice straw	Sugarcane trash
Moisture content (wt%, wet basis)	8.10	8.52	5.81
Bulk Density (kg/m³)			
Raw material	87	26	18
Pellets	579	598	717
Proximate analysis (wt%, dry basis)			
VM	81.56	69.99	57.00
FC	16.26	14.40	7.80
Ash	2.19	15.62	35.20
Ultimate analysis (wt%, dry ash-free)			
Carbon (C)	43.29	37.17	33.85
Hydrogen (H)	7.42	6.21	5.61
Nitrogen (N)	0.51	0.61	0.56
Sulfur (S)	0.03	0.06	0.10
Oxygen (O)	46.52	40.33	24.16
High heating value (MJ/kg)	16.62	13.90	10.30

First, 150 grams of sample pellets were put into the stainless steel sieve cylinder (Figure 4) of the torrefaction chamber, and the torrefaction chamber was placed manually into the torrefaction system. Then the nitrogen was supplied into the reactor at a flow rate of 1.5 L/min and the chamber was heated (heat rate $10\pm2^\circ\text{C}/\text{min}$) and maintained as such for the RT. After that, the torrefaction chamber was cooled down by nitrogen and pulled out of the system. Then the samples were taken out of the chamber and stored in zip-lock plastic bags for further analysis. In this study, the sample pellets were produced at 4 temperatures i.e., 175, 200, 225, and 250°C , and at 4 different RT i.e., 30, 60, 90, and 120 min.

Mass Yield; MY and Energy Yield; EY

The MY and EY of the torrefied agricultural residue pellets were determined as follows:

$$\text{Mass yield}(\%) = \frac{\text{Mass of torrefied solid product}(\text{kg})}{\text{Mass of originating biomass}(\text{kg})} \quad (1)$$

$$\text{Energy yield}(\%) = \frac{\text{Mass yield} \times \text{HHV of torrefied solid product}(\text{kJ/kg})}{\text{HHV of originating biomass}(\text{kJ/kg})} \quad (2)$$

Analysis of Fuel Properties

The characteristics of the agricultural residue, the agricultural residue pellets, and the torrefied pellets were in accordance with the following ASTM standards: bulk density (E 873-82), proximate analysis (D1762-84), and heating values (D2015-77); and, for the carbon, hydrogen, nitrogen, sulfur analysis, LECO Corporation standard CHNS-932. The relationship between the hydrogen/carbon and oxygen/carbon atom ratios was plotted with the Van Kravellen diagram (KVD) for the coal-band index.

Results and Discussion

Properties of Agricultural Residue

The upgrading of agricultural residue for conversion into biomass fuel will be affected by its properties. These properties vary between the different sources of the agricultural residues and these need to be understood in detail before any conversion process can be considered. The

properties that are of the greatest importance include moisture content, density, proximate analysis, ultimate analysis, and heating value. The properties of the agricultural residue under study (Table 1) are those of the biomass pellets which have a higher bulk density than the raw material, which means that the pelletization



Figure 5. Photograph of the torrefied pellets at different TT and RT; corncobs/cornhusks pellets



Figure 6. Photograph of the torrefied pellets at TT and RT; rice straw pellets



Figure 7. Photograph of the torrefied pellets at different TT and RT; sugarcane trash pellets

process is one way to upgrade agricultural residue for biomass fuel.

Effect of Torrefaction on Physical Appearance

The physical appearance of the corncobs/cornhusks (Figure 5), rice straw (Figure 6), and sugarcane trash (Figure 7) pellets at different TT and RT changed. It is evident that the color of the torrefied pellets changed from yellow to brown and became darker like charcoal as the TT and RT increased, because thermal degradation of hemicellulose occurred between 125°C and 375°C. The cellulose degradation started anywhere between 200°C and 400°C, and the lignin was relatively hydrophobic and aromatic in nature and decomposed between 175°C and 475°C (Bridgwater, 1994).

Effect of Torrefaction on Proximate Analysis

A proximate analysis is the evaluation of the yield of various products obtained upon heating under control conditions and it is important in determining the performance of any thermochemical conversion process (Cheng, 2010). The proximate analysis is used to determine the MC, VM, ash, and FC.

The MC is the amount of water in the agricultural residue expressed as a percentage of the material's weight (Cheng, 2010). It will have a significant impact on the conversion process. A high MC has an adverse effect on the storage of agricultural residue pellets, contributing to dry-matter loss through decomposition and blockages in the feeding system, and the heating value is decreased due to the energy consumption required for evaporation. The MC of the corncobs/cornhusks, rice straw, and sugarcane trash torrefied pellets (Figure 8) were lower than 2 wt% wb (wet basis) because the water had evaporated during the torrefaction process when the agricultural residue pellets were heated at a temperature of 100°C; also, the water held in the amorphous regions of the cellulosic wall ruptured the structure and then converted into steam as a result of the thermal treatment when cellulose degradation starts at 200°C (Tumuluru *et al.*, 2010). As a result, the MC of all torrefied

pellets did not have an adverse effect on the torrefied pellets' storage.

The VM of the agricultural residue's condensable and noncondensable vapor is released when the agricultural residue is heated. Its amount depends on the rate of heating and the temperature to which it is heated (Basu, 2010). The study of the proximate analysis values of the VM of the torrefied fuel through the torrefaction process at various

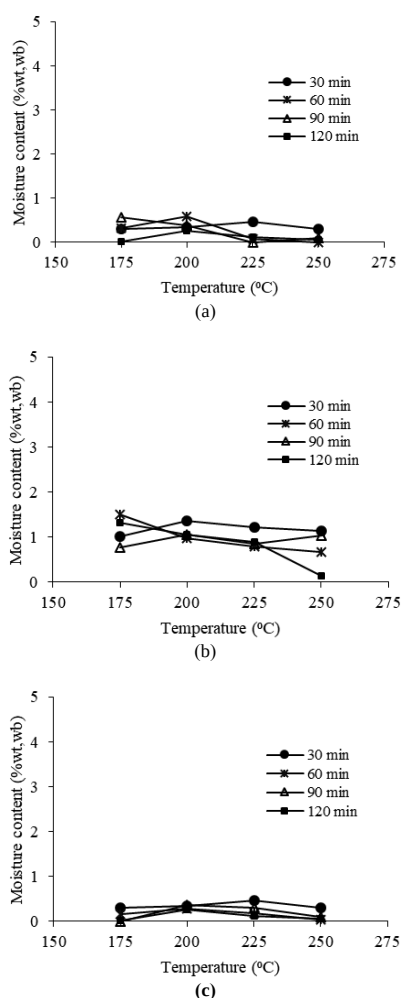


Figure 8. Effect of different TT and RT on the MC: (a) Corncobs/cornhusks pellets, (b) Rice straw pellets, and (c) Sugarcane trash pellets

temperatures and times found that the VM of the corncobs/cornhusks, rice straw, and sugarcane trash pellets (Figure 9) tended to decrease with the increased TT and RT because thermal degradation of the hemicellulose occurred with the majority of the weight loss occurring between 150°C and 280°C (Basu, 2010). In this study, increasing the TT and RT reduced the VM of the corncobs/cornhusks, rice straw, and sugarcane trash pellets by approximately 76, 81, and 76% at 250°C for 120 min, respectively.

Ash is the inorganic solid residue left after the fuel is completely burned. The ash content in wood is usually less than 1%, while it can be very high in many agricultural residues. In this study, the ash of the corncobs/cornhusks, rice straw, and sugarcane trash was approximately 2.19%, 15.62%, and 35.20%, respectively (Table 1). The ash obtained from agricultural residues' conversion does not necessarily come entirely from the agricultural residues themselves. During collection, agricultural residues are often scraped off the

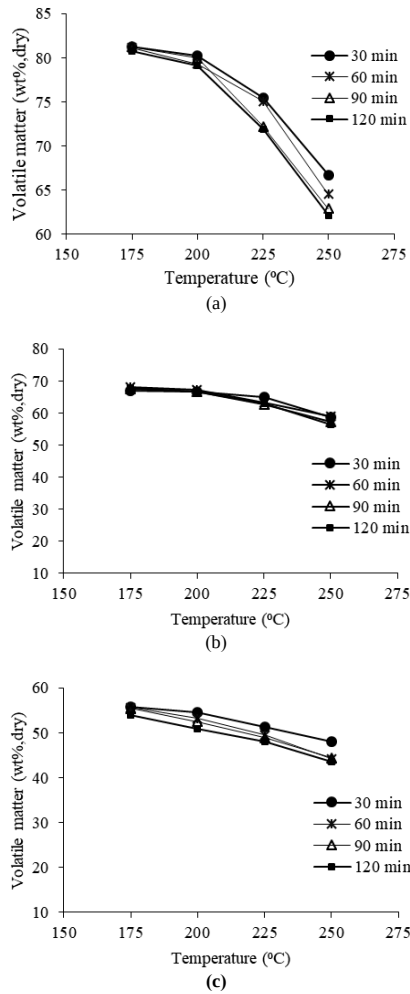


Figure 9. Effect of different TT and RT on VM: (a) Corncobs/cornhusks pellets, (b) Rice straw pellets, and (c) Sugarcane trash pellets

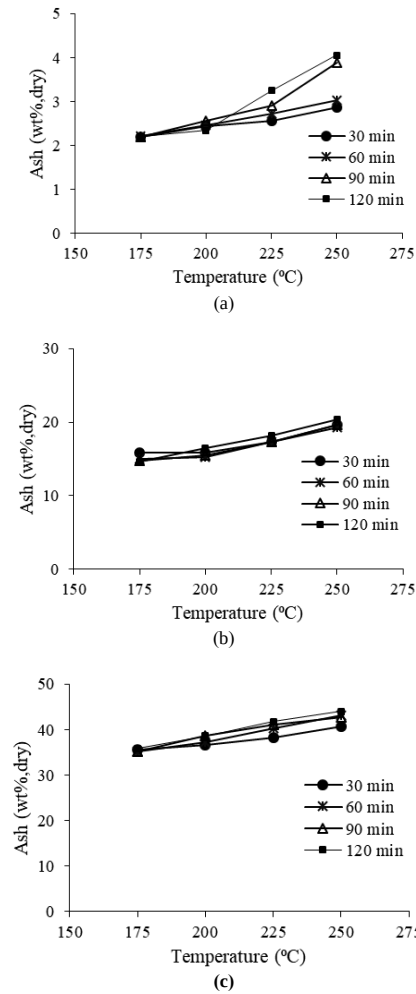


Figure 10. Effect of different TT and RT on the ash: (a) Corncobs/cornhusks pellets, (b) Rice straw pellets, and (c) Sugarcane trash pellets

ground and then undergo multiple handlings during which they can pick up a considerable amount of dirt, rock, and other impurities (Basu, 2010). The sugarcane trash in Thailand is usually collected by modified tractor that gathers impurities (soil), and then produces a high ash content. As a result, increasing the TT and RT reduces the weight of the corncobs/cornhusks, rice straw, and sugarcane trash pellets that resulted in an increase percent ash (Figure 10) that was 185%, 125%, and 131%, respectively.

The FC is elemental carbon in the original fuel, plus any carbonaceous residue formed while heating what remains in the torrefied pellets in the torrefaction process after devolatilization (Basu, 2010). The FC of the corncobs/cornhusks, rice straw, and sugarcane trash pellets increased (Figure 11) by 208%, 161%, and 164%, respectively. This same resulting trend has been seen in the proximate analysis of the torrefaction of beech wood and *Miscanthus* (Gucho *et al.*, 2015).

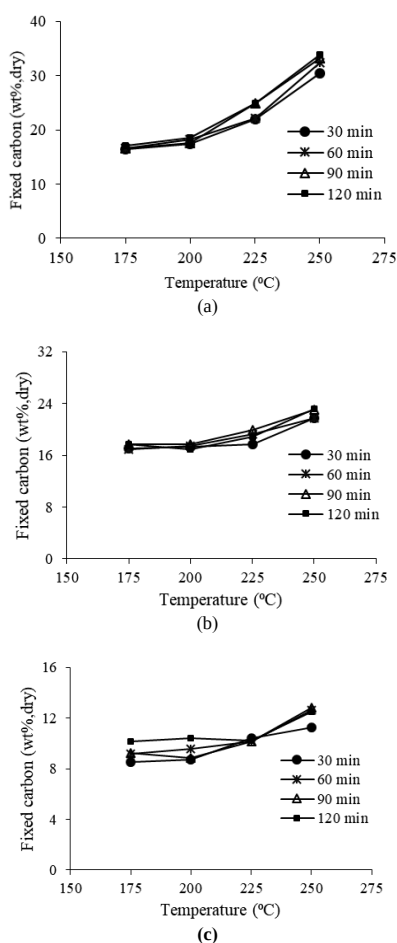


Figure 11. Effect of different TT and RT on the FC: (a) Corncobs/cornhusks pellets, (b) Rice straw pellets, and (c) Sugarcane trash pellets

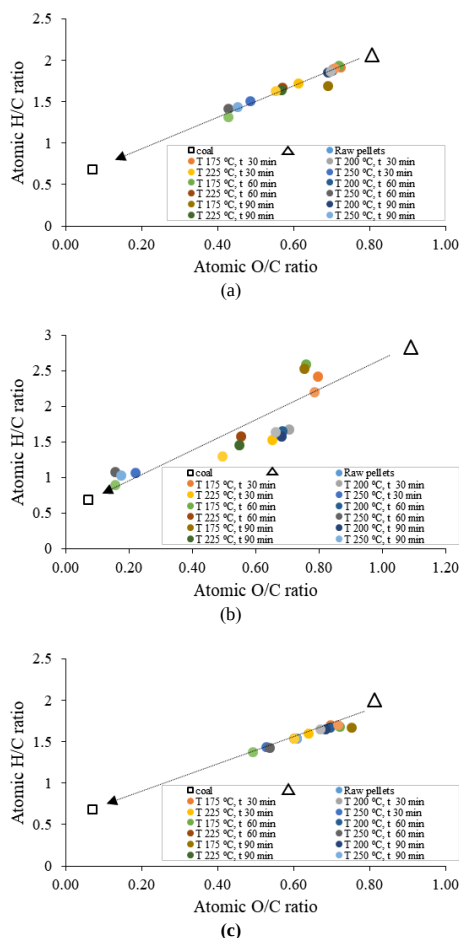


Figure 12. VKD for the raw and torrefied pellets: (a) Corncobs/cornhusks, (b) Sugarcane trash, and (c) Rice straw

Effect of Torrefaction on Ultimate Analysis

An ultimate analysis involves the determination of the element composition of the ash-free organic fraction of agricultural residues, and the major components are carbon, oxygen, and hydrogen, with a small amount of nitrogen and sulfur (Cheng, 2010). The atomic ratio is based on the hydrogen, oxygen, and carbon content of the fuel. Figure 12 plots the atomic ratio (H/C) against (O/H) on a dry ash-free basis for all torrefied pellets, raw material,

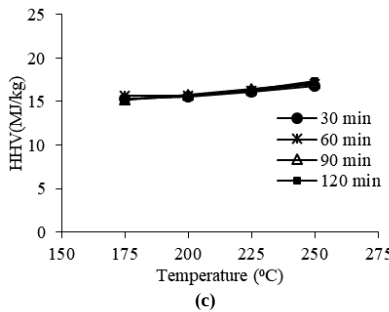
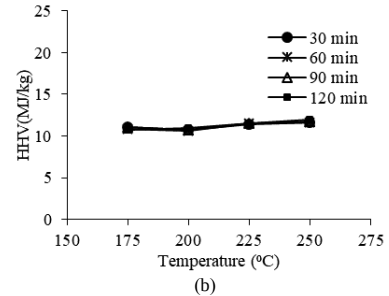
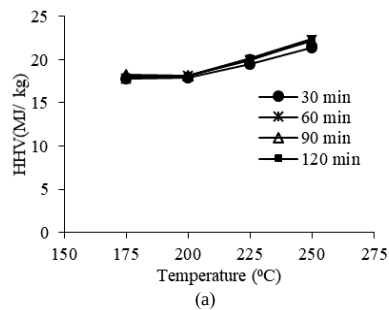


Figure 13. HHV of raw and torrefied pellets: (a) Corncoobs/cornhusks-raw pellets = 16.62 MJ/kg, (b) Sugarcane trash-raw pellets = 10.30 MJ/kg, and (c) Rice straw-raw pellets = 13.90 MJ/kg

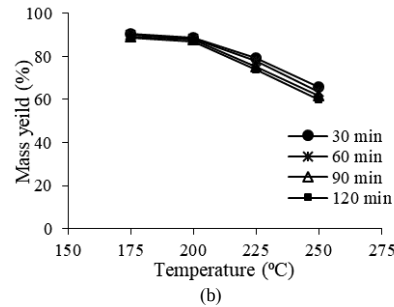
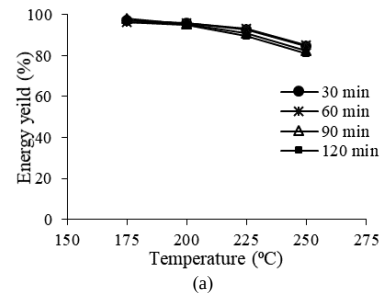


Figure 14. Yield of torrefied corncoobs/cornhusks pellets: (a) MY and (b) EY

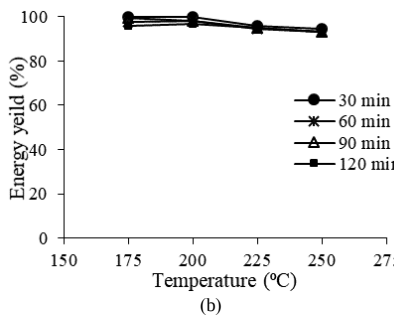
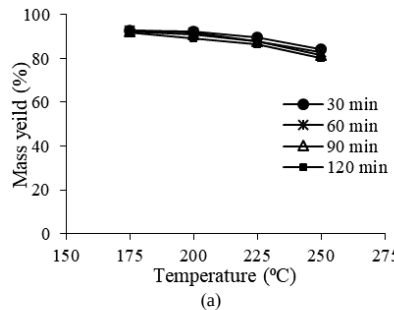


Figure 15. Yield of torrefied sugarcane trash pellets: (a) MY and (b) EY

and coal. This plot is known as the VKD (Basu, 2010). There is a linear decreasing trend of the VKD when the TT and RT increase. The decrease in those ratios provides a solid that is in the atomic ratio of coal with a higher heating value for all the pellets and correlates well with the O/C ratio. When the hydrogen-to-carbon (H/C) ratio increases, the effective heating value of the fuel reduces. In addition, the nitrogen and sulfur contents remain almost constant and do not show any tendency to have a lesser trend regarding the temperature and RT.

Effect of Torrefaction on heating value

One important property of the raw and torrefied pellets is the higher heating value, and it was found that the torrefied pellets had an increasing trend with an increase in the temperatures and RT (Figure 13). The effect of the TT is greater than that of the RT. The increased heating values of the corncobs/cornhusks, rice straw, and sugarcane trash pellets were 34, 24, and 16%, respectively. In addition, in this study with a higher TT of

250°C and RT of 120 min, the higher heating value increased to 22.40, 17.30, and 11.97 MJ/kg for the corncobs/cornhusks, rice straw, and sugarcane trash pellets, respectively. In comparison with coal, it was found that the higher heating values of the torrefied pellets are lower than that of coal (26.71 MJ/kg). The heating value in the torrefied pellets is also correlated to the presence of cellulose, hemicellulose, and lignin. Of those 3 components, lignin possesses the highest heating value, while hemicellulose has the lowest, due to its high degree of oxidation (Grammelis, 2011).

Effect of Torrefaction on Yield

Figures 14- 16 show the effects of the temperature and RT on the MY and EY of the torrefied pellets. As a result, a decrease of the MY and EY is observed as the TT and RT increase. However, the effect of the TT is greater than the effect of the RT. During torrefaction, the weight loss of agricultural residues comes primarily from the decomposition of its hemicellulose constituents. Hemicellulose decomposes mostly within the temperature range 150°C to 280°C. Lignin, the binder component of agricultural residues, starts softening above its glass-softening temperature (130°C), which helps the pelletization of torrefied agricultural residues. Unlike hemicellulose, cellulose shows limited devolatilization and carbonization which also does not start below 250°C. Thus, hemicellulose decomposition is the primary mechanism of torrefaction. At lower temperatures (<160°C), as agricultural residues dry they release H₂O (water) and CO₂ (carbon dioxide), which make no contribution to the energy in the product gas, and constitute a dominant portion of the weight loss during torrefaction. Above 180°C the reaction became exothermic, releasing gas with little heating value (Basu, 2010). This study found that the mass yields of the corncobs/cornhusks, rice straw, and sugarcane trash pellets were in the range 60-90%, 70-90%, and 80-92%, respectively, and the energy yields of the corncobs/cornhusks, rice straw, and sugarcane trash pellets were in the range 80-99%, 88-99%, and 93-99%, respectively.

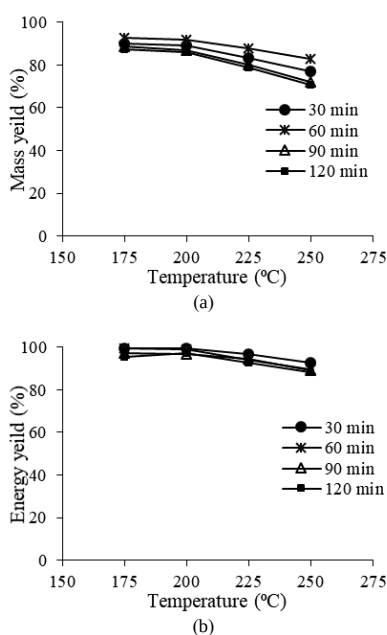


Figure 16. Yield of torrefied rice straw pellets: (a) MY and (b) EY

Conclusions

Torrefaction before the palletization process is suitable for upgrading corncobs/ cornhusks, rice straw, and sugarcane trash to high quality biomass fuel because they are nonhomogeneous and lower in bulk density than wood. When the temperature and RT are increased, a higher heating value results and there is a char product that is in the atomic ratio of coal. On the other hand, the density mass yield and energy yield are decreased; thus, consideration of this fact is important for the proportion of the optimal torrefaction condition. Optimal torrefaction conditions were produced on corncobs/cornhusks, rice straw, and sugarcane trash pellets via torrefaction when the pelletization temperature was 225°C, which provided the most suitable conditions for producing torrefied pellets; however, the RT between 30-120 min has an imperceptible effect on torrefaction before the pelletization process.

Nomenclature

TT	torrefaction temperature(s)
RT	residence time(s)
MC	moisture content(s)
VM	volatile matter
FC	fixed carbon
HV	heating value
MY	mass yield
EY	energy yield
VKD	Van Kravelen diagram

Acknowledgements

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