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Torrefaction to improve biomass pellet made of oil palm empty fruit bunch

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Abstract. This study aims at determining the effect of the torrefaction process on the fuel quality of biomass pellets made from oil palm empty fruit bunches (EFB). The torrefaction process was carried out using a rotary reactor, which has a cylinder with a diameter of 15 cm and a length of 15 cm made from an iron plate. The cylinder was heated externally using a horizontal heater fueled with LPG. The reactor cylinder was filled with 1.5 kg of clean sand to homogenize the heat transfer and prevent pellets from colliding during the process. The torrefaction process was conducted with a load of 300 grams of EFB pellets at temperatures around 240-310 °C at variations of reaction time (20, 30, and 45 min.) and the reactor cylinder rotation speed (16, 31, and 37 RPM). The results showed that the torrefaction process improved the quality of the EFB pellet fuel. This was reflected from the very low moisture content (0.32-0.52 %) of torrefied pellets and its calorific value, which increased from 15.82 MJ/kg (without torrefaction) to 17.59 MJ/kg (with torrefaction for 45 minutes). Torrefied pellets showed good hydrophobicity where the pellet was not broken when immersed in water for 24 hours. Pellet without torrefaction was destroyed in water just in one minute.

1. Introduction

Indonesia is the largest CPO producer in the world, with a contribution reaching around 60% of world CPO production. With oil palm plantation areas of 14.33 million ha, CPO production in 2018 achieved 40.57 million tons [1]. The process of extracting palm oil at a palm oil mill provides a CPO of around 21.8% [2] as the main product, plus around 13% palm kernel as an additional product. Due to its small amount, the palm kernel is usually processed in a separate palm kernel oil (PKO) mill. Besides, palm oil mill also produces a large number of wastes in the form of empty fruit bunches (EFB), fibers, palm kernel shell (PKS), and palm oil mill effluent (POME) [3]. Calculated based on the weight of the processed fresh fruit bunch (FFB), each ton of FFB will produce around 200-230 kg of empty fruit bunches (EFB), 50-60 kg of the shell, 120-130 kg of fiber, and 0.77-0.84 m^3/ton of palm oil mill (POME) [2]. The amount of EFB waste is proportional to the amount of CPO product. This means that in 2019 there will be around 40 million tons of EFB in Indonesia. EFB is a waste with a high water content reaching 60% [4] to 64.17% [6]. Some palm oil mills are equipped with shredder machines to rip and squeeze EFB, and the water content in the EFB is reduced to around 40%. In general, the EFB is returned to the plantation, both as mulch or compost after EFB composting process. Composting of

EFB through open windrow method which watered with POME every another day can reduce methane emissions up to 35.92% for the composting duration of 30 days and 53.22% for 80 days period [7]. Application of EFB into plantations can return carbon and soil nutrients because EFB has 42% C, 0.8% N, 0.06% P, 2.4% K and 0.2% Mg [5].

The problem is that not all palm oil processing factories have their own plantations that can accommodate EFB. It is estimated that currently, there are around 20% of palm oil processing factories that only rely on fruit supply from partnering farmers and do not have their own plantations, which means covering approximately 2.8 million ha of plantations or the equivalent of eight million tons of EFB in the year 2019. Therefore, there has to be a better alternative to handle the EFB. Recently our team reported that EFB could be used as a medium for mushroom cultivation [8]. Field surveys around palm oil mills operating in East Lampung (Indonesia) show that mushrooms' cultivation using EFB media provides high income for farmers. However, this practice only covers a small part of the available EFB. Consequently, it is urgent to promote more environmentally friendly ways of utilizing the EFB to improve the sustainability of palm oil industries. Densification of EFB into pellets is one alternative that needs to be considered for EFB utilization.

With high water content, EFB is challenging to be used as fuel. In dry conditions, EFB has a calorific value of about 13.82 MJ/kg [9], so that it has the potential as a source of energy. However, EFB is very bulky because it has a low bulk density of around 555 kg/m^3, which will make it difficult to handling and need more transportation cost. One alternative for the utilization of EFB for energy sources is to change the physical EFB into more compact pellets. Suppose the pelletizing process is carried out around a palm oil processing plant. In that case, the EFB drying can utilize the flue gas's waste heat or residual heat of steam resulted during the crude palm oil extraction process. Densification of EFB at a pressure of 55 MPa can produce good EFB pellets with bulk density reaching about 1.5 t/m^3 [10]. Nevertheless, this pellet still has shortcomings because it is easily damaged when stored in open spaces since the pellets are still hygroscopic, making it easy to absorb moisture from the environment. In addition, heat is released from large-scale biomass pellet piles due to microbial, chemical, and physical processes that may trigger an open burning. In the early stages, the microbial processes proved to be the most important contributor to heat production during biomass storage [11].

One way to improve the nature of biomass pellets is to use a torrefaction treatment. Torrefaction is a thermochemical process carried out at temperatures between 200 to 300°C in conditions without oxygen [12]. It was recently reported, however, that oxidative torrefaction carried out in the presence of limited oxygen has a positive effect on the torrefaction process [13]. The process will produce torrefied biomass, which has hydrophobic properties so that the pellet is not easily damaged during storage. Besides, the torrefied biomass also has a higher calorific value than biomass without torrefaction. This study aims to determine the effect of torrefaction treatment on the fuel quality improvement of the EFB pellet.

2. Materials and methods

2.1. Materials

The EFB pellet (Figure 1) was obtained from the commercial pellet industry in Tebing Tinggi, North Sumatera. The pellet has a hexagon-shaped cross-section with an average diameter of 9.65 mm and a mass density of 1.39 g/cm^3. Pellets were sorted to obtain samples with a length of 1-3 cm used in this study. The characteristics of the EFB pellet was given in Table 1.

Figure 1. EFB Pellet used in the experiment

Table 1. Characteristic of EFB pellets.

Parameter	Value
Color	Dark brown
Cross-section	Hexagonal
Diameter	9.65 mm (average)
True density	1.39 kg/cm^3
Bulk density	600 kg/m^3
Moisture content (wb)	7.96%
Ash content	12.36%
Calorific value	15.82 MJ/kg

2.2. Torrefaction Process
The EFB pellet torrefaction process was carried out using a cylindrical reactor with a diameter of 15 cm and a length of 15 cm made of iron plates (Figure 2). The reactor is heated from the outside using a horizontal LPG-fueled heater and equipped with an electric motor to rotate the cylinder. The cylinder rotational speed can be adjusted using a potentiometer. In this research, the torrefaction process was carried out with speed variations between 18 to 37 RPM in a 20 to 45 minutes duration process. Each experiment was carried out with 300 grams of pellet samples and was replicated three times to get an average value. During the torrefaction process, the collisions between pellets and cylinder wall can cause damage to the samples. Therefore, sieved clean sand was filled into the cylinder to avoid the damage of pellets. Each experimental unit was carried out by first heating the reactor for 20 minutes to reach a temperature of around 200 ℃ and then hold according to the planned time, 20, 30, and 40 minutes.

2.3. Analysis and Measurements
Characteristics of pellets included water content, bulk density, solid density (true density), calorific value, ash content, water absorption, and hydrophobicity properties. Water content is measured gravimetrically by drying it in an oven (Memmert UM 500) at 105 °C for 24 hours. Water content (*WC*) is calculated from:

$$WC = \{(M_i - M_f)/M_i\} \times 100\% \quad (1)$$

where M_i and M_f are pellet mass before and after drying, respectively.

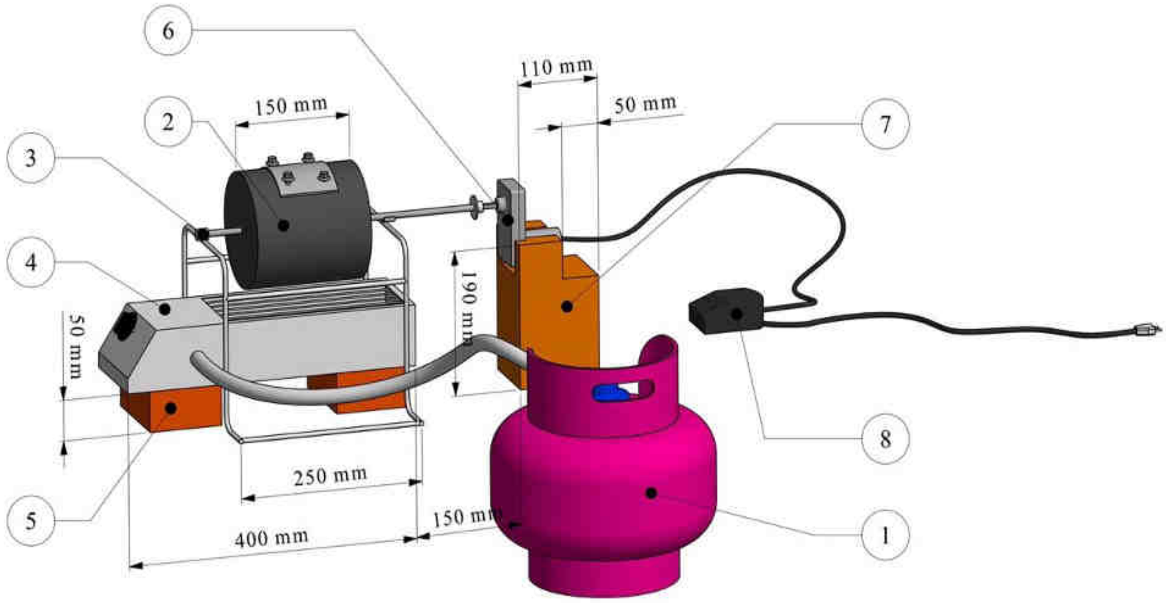

Figure 2. Schematic picture of a rotary torrefaction reactor: 1. LPG bottle, 2. Rotary reactor with variable speed, 3: Shaft with quick coupling to an electric motor, 4: LPG fueled heater, 5: Heater support, 6: Electric motor with variable speed, 7: motor support, 8: AC to DC adapter

Oven-dry pellets were used as samples to measure the calorific value and ash content. The pellet's calorific value was measured using a bomb calorimeter (Cal2k ECO), which was calibrated using a benzoate pill. The ash content was measured by burning pellets using a furnace (Ney Vulcan 550) at 550 °C for 2 hours. Ash content is expressed as a percent of the oven-dry mass of the pellet.

The hydrophobicity of pellets was measured by immersing the pellet in water and observing its changes for 24 hours. Water adsorption was measured by leaving the oven-dry pellets in an open container and observing the change in its mass for a particular time (11 days).

Three parameters were employed to evaluate torrefaction results, namely mass yield (Y_m), the ratio of energy value (E_r), and energy yield (Y_e). The energy ratio is also called energy density [14]. The three parameters were calculated according to formulas proposed by Uemura et al. [15] as the following:

$$Y_m = (m_t/m_i) \times 100\% \quad (2)$$

$$Y_e = Y_m \times E_r = [(m_t \times CV_t) / (m_i \times CV_i)] \times 100\% \quad (3)$$

$$E_r = CV_t / CV_i \quad (4)$$

where m was the mass of the pellet, and CV was the calorific value of the pellet. The subscript i was for initial and t for torrefied pellet.

3. Results and Discussion

The measurement results show that the temperature of the torrefaction process is influenced by time. The longer the torrefaction time, the higher the temperature the reactor can reach. Based on observations, the torrefaction temperature reached 240 ℃, 280 ℃, and 310 ℃ in each 20, 30, and 45 minutes. These results show that the temperature increase of torrefaction is following the accumulated heat. The longer the heating, the more heat is given, and the higher the temperature can be achieved.

Figure 3 shows some pellet samples from torrefaction results in 10 to 45 minutes. When compared to the original pellet (Figure 1), the torrefaction pellets have a darker color. However, some torrefaction pellets samples with a time of 10 minutes still have a relative brown color. The color change to darkening is caused by the carbonization process that occurs during torrefaction.

W2T1 W2T2 W3T3

Figure 3. Example of torrefied pellets with torrefaction duration of 10 min (T1), 20 min (T2), and 10 min (T3)

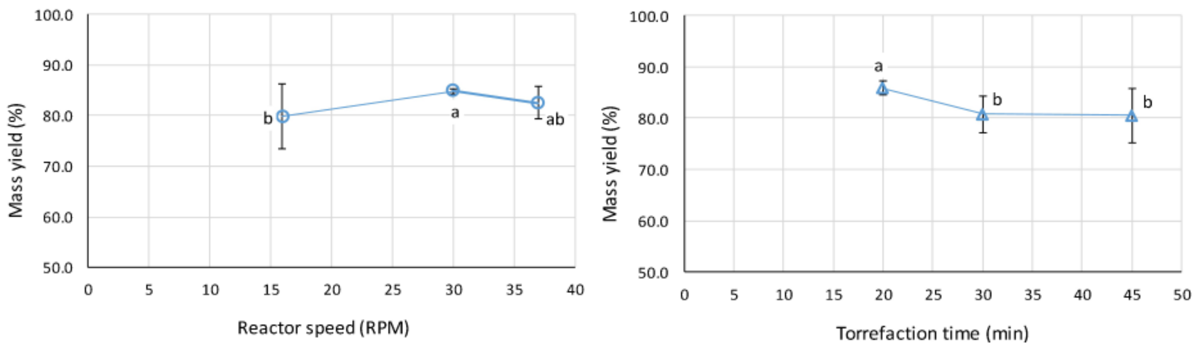

Figure 4. Effect of reactor speed (left) and torrefaction duration (right) on the mass yield. (Points followed by common letters are not statistically different at 5%. Error bars are standard deviation from three measurements.)

After torrefaction, the resulting pellet mass yield decreased from the initial pellet mass. The mass yield was in the range of 80 to 86%. Theoretically, the mass yield from the torrefaction process is 70% [16]. Therefore, our torrefaction process can still be improved to optimum conditions. Mass reduction is caused by the fact that the generated heat evaporates the water and volatile components during the torrefaction process. Statistically, both the duration of the torrefaction process and the reactor rotational speed significantly influence the pellet's mass yield. However, the interaction of the two factors has no significant effect on the mass yield. Figure 4 reveals that mass yield decreases with increasing processing time. This decrease can be understood because the longer the heating process is carried out, the more volatile content evaporates. In contrast, the rotational speed is the opposite. The slower the reactor speed, then the mass yield will be lower. This happens because the slower the reactor spins, the longer the pellet comes in contact with the hot sand so that more water and volatile components evaporate. But in Figure 4, it can be seen that above the speed of 30 RPM, there is a tendency for mass yield to fall. This mass decrease is thought to be caused by the collision between the pellet and the cylinder wall as the reactor rotates faster.

The Torrefaction process has also resulted in changes in pellet density. Without torrefaction, EFB pellets have a bulk density of 0.43 g/cm^3 and a true density of 1.49 g/cm^3. The rotational speed of the reactor has a significant effect on the true density pellets. Likewise, the duration of the torrefaction process. The interaction of the two factors, however, has no important effect. Figure 5 shows that the torrefied pellets' true density dropped between 1.18 and 1.35 g/cm^3. This decrease occurs due to the loss of water and volatile components in the pellets during the torrefaction process so that the individual pellets become lighter. The torrefied pellets have a narrower bulk density range from 0.34 to 0.37 g/cm^3, slightly lower than the bulk density of EFB pellets without torrefaction (0.43 g/cm^3).

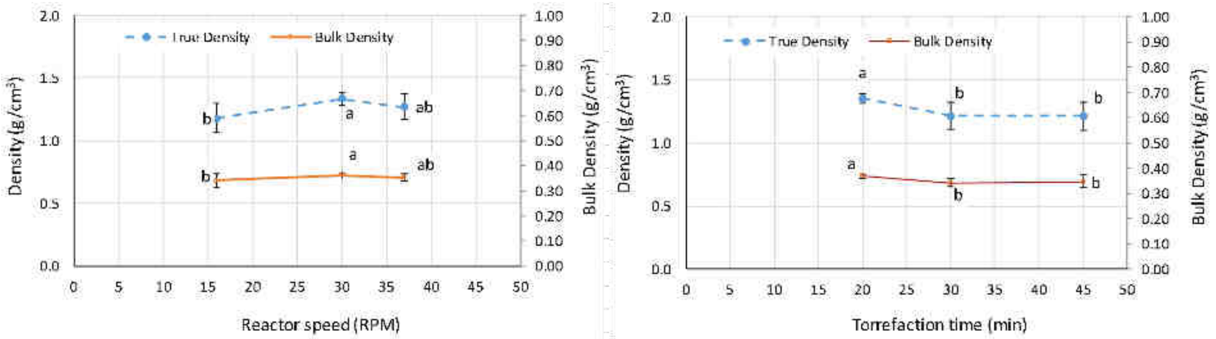

Figure 5. Effect of reactor speed (left) and torrefaction duration (right) on the density of torrefied pellets (points followed by common letters are not statistically different at 5%. Error bars are standard deviation.)

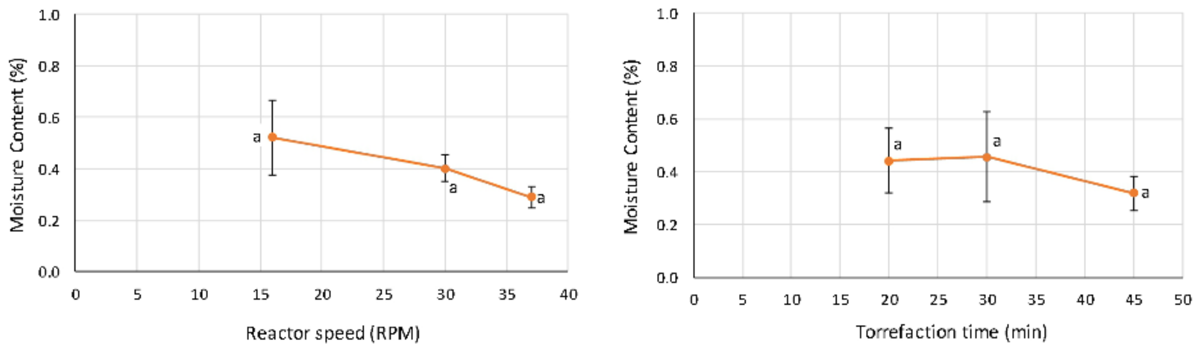

Figure 6. Effect of RPM (left) and torrefaction duration (right) on torrefied pellets' moisture content. (Points followed by common letters are not statistically different at 5%. Error bars are standard deviation.)

Figure 6 reveals that during the torrefaction process, the water content of the pellet dropped to between 0.32% (wb) to 0.52% (wb), which means a decrease of 93.5% to 96.0% from the initial water content of 7.96% (wb). Both factors (rotational speed and duration of torrefaction) statistically have no significant effect on the torrefied pellets' water content. This means that torrefaction for 20 minutes succeeded in evaporating almost all of the pellet's water content. Visually the longer torrefaction process will produce biomass with a darker color, as previously shown in Figure 3.

Figure 7 shows the pellet characteristics before and after the reaction process to its ability to absorb moisture from the surrounding air. It can be seen that torrefaction pellets absorb water from the ambient air up to around 6.5%, while pellets without torrefaction can absorb water up to almost 9%. This implies that torrefied pellets will have a longer period in storage.

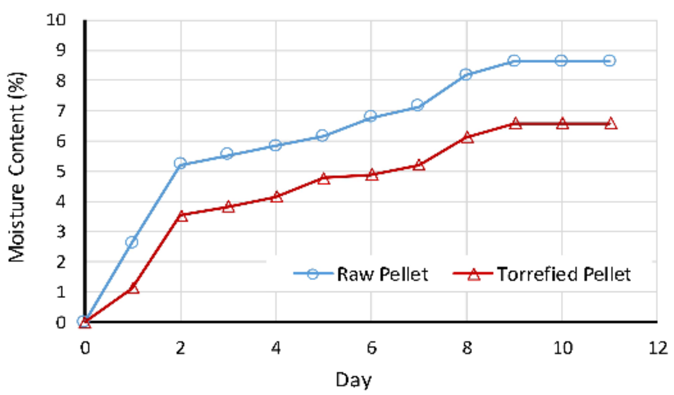

Figure 7. Absorptivity of pellets toward moisture in the ambient air

Figure 8 shows that torrefied pellets have ash content between 15.50 and 17.71%. Both factors (reactor rotational speed and length of the torrefaction process) and their interactions have no significant effect on torrefied pellets ash content. Compared with the original ash pellets (12.36%), the torrefaction pellet ash content is higher. Increased ash content occurs due to reduced volatile components in hemicellulose and cellulose, which evaporate during the torrefaction process. Reference [17] reported that during torrefaction of oil palm fiber, the hemicellulose degradation begins at 275 °C. Other work reported that the torrefaction of EFB pellets in an oxidative environment using electric furnaces at 280 °C with a residence time of 20 minutes caused the hemicellulose content to decrease to 15% cellulose decreased to 27% [18].

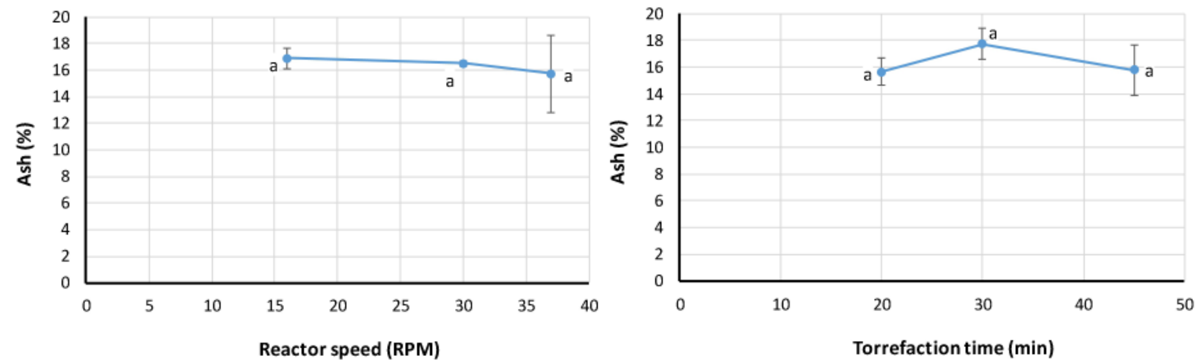

Figure 8. Effect of RPM (left) and torrefaction duration (right) on the ash content of torrefied pellets. (Points followed by common letters are not statistically different at 5%. Error bars are standard deviation.)

Increased ash content is not good for fuel. This is because high ash content will have implications for decreasing fuel calorie value [19]. Another negative effect of high ash content is mineral content, which can cause slagging and fouling problems in thermal conversion systems involving high temperatures such as boilers.

Figure 9 shows the torrefaction pellet's energy value, ranging from an average of 16.66 to 17.74 MJ/kg. Compared with the energy value of untorrefied pellets (15.82 MJ/kg), pellets' energy value has increased between 5 to 11%. The increase in energy value is due to the volatility of some of the volatile components resulting in a decrease in the ratio of oxygen to carbon (O/C). As it is well known that the energy value of a fuel is related inversely to the O/C ratio. The calorific value of biomass is higher with the lower O/C ratio, and vice versa.

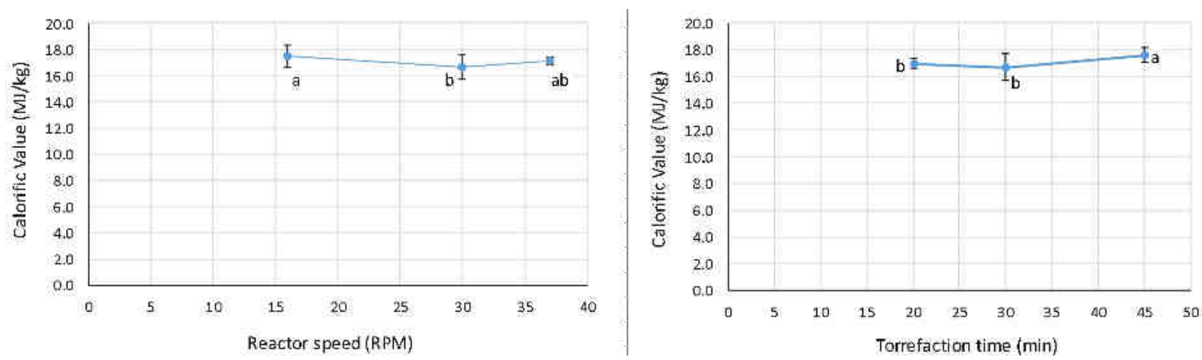

Figure 9. Effect of RPM (left) and torrefaction duration (right) on the calorific value of torrefied pellets. (Points followed by common letters are not statistically different at 5%. Error bars are standard deviation.)

Based on these energy values, energy yield, and energy density can be calculated using Equations (3) and (4). Although the caloric value increases, as given in Figure 10, the energy yield drops to between 85 and 92% compared to the raw pellet energy fed in the torrefaction process. This decrease occurs because the torrefied pellet mass has decreased so that the multiplication between mass and energy value results in a decreased energy yield value. Theoretically, Basu states that the torrefaction process's energy yield is 90% compared to the initial energy value [16]. Figure 9 also shows the value of energy density or energy ratio resulting from the torrefaction process with a narrow range of values between 1.05 and 1.11, which means an increase of between 5 and 11%. Basu [16] states that the energy density of the biomass torrefaction process can reach 1.3 or an increase of 30%. This indicates that the torrefaction process we carried out has not achieved optimal results yet.

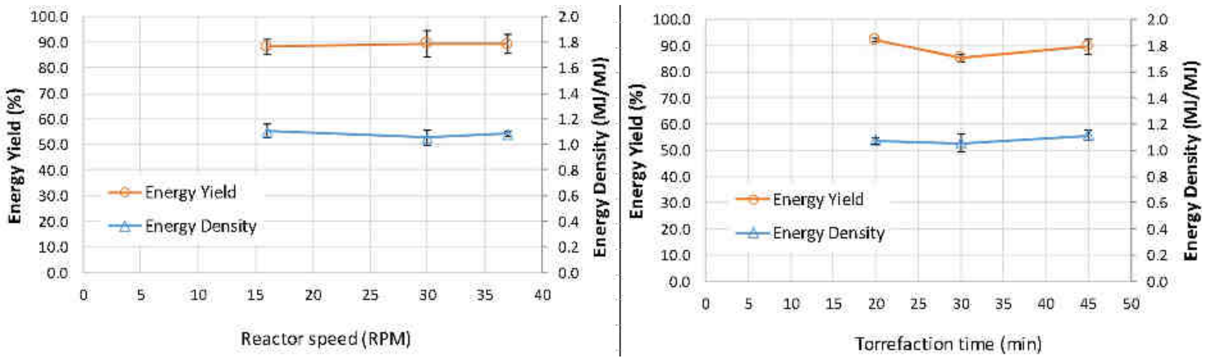

Figure 10. Effect of RPM (left) and torrefaction duration (right) on the energy yield and energy density of torrefied pellets. (Error bars are standard deviation.)

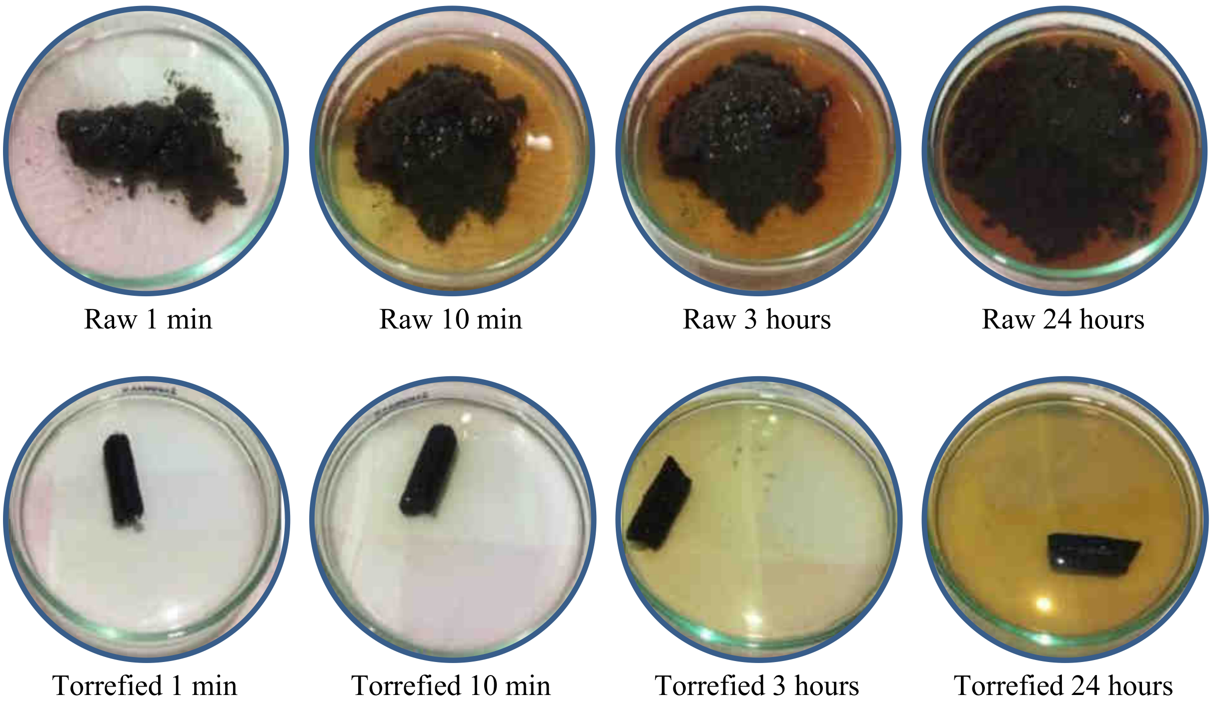

Figure 11. Pellet endurance in terms of hydrophobicity. (Top: raw pellet, Bottom: torrefied pellet)

The most striking advantage of torrefaction pretreatment is that it changes the hydrophilic pellet to hydrophobic. Hydrophilic biomass can cause problems, especially in large-scale storage for stock purposes. Flammable materials such as coal and biomass, which are stacked (stored) in specific volumes and durations, can experience fires due to spontaneous combustion triggered by heat generated from condensation and biochemical oxidation reactions [20]. The event of biomass fires in storage that occurred in the period 2000-2018 has been reported by [21], which recorded 69 cases in the Americas and Europe. Therefore, changing the hygroscopic nature of EFB pellets into hydrophobics is very important to prevent fire hazards during storage. In general, decreasing water content during torrefaction provides three main benefits, namely: reducing the humidity for the conversion process, reducing transportation costs associated with reducing biomass weight, and preventing biomass decomposition and water adsorption during storage and transportation [13].

Figure 11 shows the superiority of torrefied pellets as compared with untorrefied ones in terms of their hydrophobicity. In extreme conditions immersed in water, pellets without torrefaction immediately absorb water and disintegrate in just one minute. On the other hand, the torrefaction pellet showed no change after soaking for 3 hours. Even after 24 hours, the pellets are still intact. Only the color of the water begins to turn yellow due to the dissolution of the volatile component. This shows that the torrefaction process produces hydrophobic biomass and can last a long time in storage.

4. Conclusion

We have treated the reaction of EFB pellets using a rotary reactor that works at temperatures between 240 and 310 °C. The results showed that the torrefaction process produced a better solid biomass fuel. The torrefaction process improved the quality of the EFB pellet fuel by decreasing water content from 7.96% (raw pellets) to 0.29–0.54% (torrefied pellets) and increasing calorific value from 15.82 MJ/kg (raw pellets) to 17.59 MJ/kg (torrefied pellets). Torrefied pellets showed good hydrophobicity where pellets withstand in the water for 24 hours. Pellets without torrefaction were destroyed in water in just one minute. Based on the above discussion, the torrefaction time for 20 minutes can be chosen.

Acknowledgments

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