Utilization of oil palm empty fruit bunches biomass through slow pyrolysis process

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Abstract. The agricultural sector produces solid waste biomass abundantly. However, this biomass potential has not been utilized optimally. Indonesia as the world's number one producer of oil palm plantations produces enormous biomass potential. Oil palm empty fruit bunches (EFB) are the largest solid waste with a fraction of around 20-23% of fresh fruit bunches. Conventionally, it is only used as plant mulch in plantations areas. However, this biomass can still provide added value to bioenergy products through thermochemical pyrolysis conversion. The study was conducted with EFB raw materials that have been chopped with a size of <2mm, heating rate of 10°C/minute with temperature variations of 350°C, 400°C, 450°C, 500°C, and 550°C. The results showed that the EFB pyrolysis at low temperatures produced biochar products, at high temperatures, it produced maximum product in the form of bio-oil. In the EFB pyrolysis process, biochar with an optimum yield of 36.92% was produced at 350°C, and bio-oil with an optimum yield of 46.60% was produced at a temperature of 550°C.

1. Introduction
The extent of oil palm plantation land makes Indonesia becoming the largest palm oil producer in the world. The total area of oil palm plantations reached 11.26 million hectares in 2015 and was expected to be 12.31 million hectares in 2017. The total palm oil production produced was 31.07 million tons and the palm kernel was 6.21 million tons [1]. The amount of productivity of palm oil has the potential as a source of biomass waste. Production activities in oil palm agro-industrial in addition to producing the main product also producing byproducts, namely solid waste. Various types of solid waste are generated from the activities of palm oil processing plants and from plantation activities. Palm Kernel shells, mesocarp fibers, and empty fruit bunches are the main solid waste produced during the milling process while leaves and stems are obtained from plantations in the harvesting, pruning, and logging process [2]. EFB biomass is the waste with the largest fraction (20-23% of FFB). Biomass waste is the fourth largest source of energy after coal, petroleum, and natural gas so it can contribute greatly to the supply of renewable and sustainable energy sources. Utilization of this waste can be done by conversion through thermochemical processes, namely pyrolysis.

The utilization of conversion technology needs to be applied in accordance with the characteristics of biomass. Palm oil biomass waste contains hemicellulose, cellulose, and lignin with varying
compositions. Biochemical processes are not suitable for palm oil biomass waste because its characteristics are lignocellulosic materials with a high enough lignin content that it is more difficult to be degraded [3]. Conversion technology that can be applied is a thermochemical conversion technology namely pyrolysis. Thermochemical conversion is preferred because biological conversion will be more difficult with the characteristics of complex structures and biomass chemical mechanisms [4]. The pyrolysis process can convert raw materials containing cellulose components as much as 81.41% and 44.2% hemicellulose into bio-oil while 40.33% lignin will become char [5].

Research related to the conversion of biomass to bioenergy through the thermochemical pyrolysis conversion process has been widely conducted by researchers with various variations. Pyrolysis research uses different types of biomass such as biomass residue of pyrolysis or Euryale ferox [6], orange peel biomass [7], wood waste of Paulownia elongate [8], empty fruit bunch (EFB) [9], soybean stover and peanut shells [10], sawdust and giant Miscanthus [11], safflower seed [12], peanut and soybean skins [10], etc. The researchers mostly analyzed and reviewed factors that affected the pyrolysis conversion process: temperature, heating rate, particle size, residence time, raw material characteristics [13] [14] [15] [16] [17]. Analysis was also performed on the characteristics of the bio-oil product, the resulting biochar [18] [19] [20] [21] [22] [23].

Pyrolysis research with EFB raw materials was conducted by [24] using high temperatures of 450-800°C, [20] at 460-520°C, and [25] at 352-452°C. In this study, the study was conducted in the low to high temperature range to determine the effectiveness of temperature against the resulting product. So, it can provide input to the selection of the right operating process to produce the desired product in accordance with the characteristics of EFB raw materials. With the abundant volume of EFB biomass produced by the palm oil industry but its utilization is not optimal yet, this study becomes important. Pyrolysis technology as a method of converting EFB into new products can be used as an alternative solution for the utilization of EFB in the future.

2. Materials and Methods

2.1. Raw Material
EFB raw materials were taken from the palm oil mill of PT. TSB in Saliki Village, Muara Badak Subdistrict, Kutai Kartanegara Regency. Early characteristics of EFB analyzed included chemical components (cellulose, hemicelluloses, and lignin), ultimate analysis (C, H, O, N) proximate analysis (fixed carbon, volatile matter, ash levels, moisture content, and HHV). Then EFB was chopped with a size of <2mm and then tested the size distribution. After that, the EFB was dried for 24 hours until the water content was <10%.

2.2. Pyrolysis Reactor
The pyrolysis reactor consisted of a tube with a capacity of 0.4kg with dimensions of 0.5m and a diameter of 0.15m equipped with a jacket. Pyrolysis outlet reactors were connected with condensers used to condense pyrolysis gases into bio-oil.

2.3. Pyrolysis Experiment

This study used EFB raw materials as much as 400 grams according to the capacity of the pyrolysis reactor. Pyrolysis raw materials that have undergone a pretreatment process with the process of enumeration and drying were incorporated into the reactor. Pyrolysis surgery was carried out with temperature variations of 350 °C, 400 °C, 450 °C, 500 °C, and 550 °C and the heating rate of 10 °C / minute. The resulting products in the form of biochar and bio-oil were tested characteristically based on proximate and ultimate tests. The production of biochar, bio-oil, and gas was calculated based on the equation:

\[
\text{The char yield} = \frac{\text{mass of char (g)}}{\text{mass of EFB (g)}} \times 100\% \tag{1}
\]
The bio-oil yield = \( \frac{\text{mass of bio-oil (g)}}{\text{mass of EFB (g)}} \times 100\% \) ................................................ (2)

The gaseous yield = 100% – oil yield – char yield ......................... (3)

3. Results and Discussion

3.1. Characteristic of EFB

Knowledge of the characteristics of EFB raw materials is essential in the optimization and the efficiency of thermochemical conversion processes. The proximate, ultimate, and chemical characteristics of EFB in this study are shown in table 1 column a). Some studies have been conducted by [26] [27][28] [20] [13] [17][29][11][22][30][18][19] on the raw material of EFB as shown in Table 1.

| EFB Characteristic | Reference | Average | StDev |
|--------------------|-----------|---------|-------|
|                    |           |         |       |
| Proximate          |           |         |       |
| Volatile matter    | 81.90     | 80.89   | 72.88 |
| Fixed Carbon       | 12.60     | 12.60   | 12.56 |
| Ash                | 3.10      | 4.02    | 11.10 |
| Moisture           | 2.40      | 2.40    | 3.47  |
|                   |           |         |       |
| Ultimate           |           |         |       |
| C                  | 53.78     | 44.71   | 55.89 |
| H                  | 4.37      | 6.76    | 6.31  |
| O                  | 41.50     | 42.44   | 42.99 |
| N                  | 0.35      | 0.21    | 0.60  |
| S                  | 0.41      | <0.1    | 1.06  |
|                   |           |         |       |
| Caloric value      | 17.08     | 16.83   | 16.96 |
| HHV MJ kg⁻¹        | 21.77     | 19.65   | 20.85 |
| LHV MJ kg⁻¹        | 17.47     | 17.47   |
|                   |           |         |       |
| Lignocellulose     | 3.72      | 7.52    | 11.11 |
|                    |           |         |       |

The average data obtained was the empirical formula of EFB namely CH_{1.52}O_{0.69}N_{0.008}. Proximate analysis showed that raw EFB fiber has a rather high volatile content, moderate levels of ash content, and a relatively low fixed carbon content. But the elemental analysis showed that raw EFB fiber is an environmentally friendly material with a small nitrogen and sulfur content. The water content of raw EFB is so high (49.64%) that it requires pretreatment before converting the pyrolysis process.

FB raw materials were taken from the palm oil mill of PT. TSB in Saliki Village, Muara Badak Subdistrict, Kutai Kartanegara Regency. Early characteristics of EFB analyzed included chemical components (cellulose, hemicelluloses, and lignin), ultimate analysis (C, H, O, N) proximate analysis (fixed carbon, volatile matter, ash levels, moisture content, and HHV). Then EFB was chopped with a size of <2mm and then tested the size distribution. After that, the EFB was dried for 24 hours until the water content was <10%.

3.2. Influence of temperature to pyrolysis product

Pyrolysis uses EFB as raw material at various temperature variations over the resulting product as shown in Table 2 and Figure 1.
The analysis data shows that biochar is formed maximum at low temperatures of 350-400 °C and will decrease along with the increase in temperature. While bio-oil is formed at a higher temperature of 500-550 °C and will decrease along with the increase in temperature. Several studies have also shown similar patterns in temperature parameters and residence time [15]. In one of the studies of [32], the bio-oil yield of 27% at 400 °C increased to 54% at 550 °C and decreased to 51% at 600 °C. The study of [10] using bean and soybean peels produced 36.91% of biochar and 37.03% at 300°C. Besides, the study of [33] using tea tree branches showed a yield of 47.94% at 300°C. Moreover, the study of [34] using wood pallet raw materials and spruce wood slats showed a temperature condition of 350 °C as the optimal temperature by producing >40% of biochar yield. Research using EFB also showed similar results, including the study of [26] where at 300°C, it produces biochar yields of 41.56%, the study of [21] in which at 350°C, it produces biochar yields of 37.57%, and research of [9] where it produces a yield of >30% at 450°C. While the study of [35] shows that it produces the highest bio-oil yield of 47% at 500 °C.

The pyrolysis reactor consisted of a tube with a capacity of 0.4kg with dimensions of 0.5m and a diameter of 0.15m equipped with a jacket. Pyrolysis outlet reactors were connected with condensers used to condense pyrolysis gases into bio-oil.

### 3.3. Characteristic pyrolysis product

Table 3 is a biochar characteristic of EFB raw materials resulting from pyrolysis processes. The main factors that influence the formation of biochar yields are temperature, residence time, and biomass.

### Table 2. Results of Measurement and Calculation of Pyrolysis Product Yield

| Temperature (°C) | Bio-oil Measurement (g) | Biochar measurement (g) | % Bio-oil yield | % Biochar yield | % Gas yield |
|------------------|-------------------------|-------------------------|----------------|----------------|-------------|
| 350              | 13.26                   | 147.66                  | 32.82          | 36.92          | 30.27       |
| 400              | 132.06                  | 130.64                  | 33.02          | 32.66          | 34.33       |
| 450              | 142.97                  | 105.41                  | 35.74          | 26.35          | 37.91       |
| 500              | 180.06                  | 112.43                  | 45.02          | 28.11          | 26.88       |
| 550              | 186.40                  | 112.09                  | 46.60          | 28.02          | 25.38       |

**Figure 1. Slow Pyrolysis Product Yield**

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**Table 3. Biochar characteristic of EFB raw materials resulting from pyrolysis processes.**

| Temperature (°C) | % yield Bio-oil | % Yield Biochar | % Yield Gas |
|------------------|-----------------|-----------------|-------------|
| 300°C            | 32.82           | 36.92           | 30.27       |
| 400°C            | 33.02           | 32.66           | 34.33       |
| 450°C            | 35.74           | 26.35           | 37.91       |
| 500°C            | 45.02           | 28.11           | 26.88       |
| 550°C            | 46.60           | 28.02           | 25.38       |
composition. Slow pyrolysis with heating rate and low gas flow is perfect for biochar formation. Characteristics of biomass with low water content, high lignin, large particle size are highly recommended to increase biochar yield (Tripathi et al., 2016). Biomass raw materials that are high in cellulose are highly recommended if people want to obtain bio-oil products and biomass containing high lignin for high biochar production (Zaman et al., 2017). The resulting biochar characteristics allow it to be used as a soil amendment. Besides, it can also be used as an active carbon forming material through the activation process.

Table 3. Characteristic of Biochar

| Parameter | Percent % | Operation Temperature | | | |
|---|---|---|---|---|---|
| | 350°C | 400°C | 450°C | 500°C | 550°C |
| C | 48.21 | 47.00 | 45.24 | 44.82 | 48.84 |
| O | 47.00 | 45.24 | 44.82 | 48.84 | |
| H | 5.54 | 5.40 | 5.20 | 5.15 | 3.26 |
| N | 0.367 | 0.257 | 0.425 | 0.355 | 0.835 |
| S | - | - | - | - | - |
| K | 3.190 | 2.856 | 4.115 | 4.412 | 2.569 |
| Ca | 1.666 | 0.854 | 0.785 | 0.481 | 0.387 |
| Mg | 0.645 | 0.584 | 1.037 | 1.164 | 0.931 |
| Si | 7.46 | 9.22 | 10.87 | 12.99 | 35.06 |
| P | 0.576 | 0.618 | 0.839 | 1.108 | 0.931 |
| Na | 0 | 0 | 0 | 0 | 0.153 |

The parameter of the residence time has no significant effect on the characteristics of the calorific value of bio-oil [15]. As data on some characteristics of EFB bio-oil obtained from pyrolysis processes as shown in Table 5.7, the quality is lower when compared to the characteristics of fuel oil. Bio-oil of EFB has pH, moisture content, ash content, and calorific value that are not as good as fuel oil [14] [13], and diesel fuel [18]. So, bio-oil still requires upgrading if it will be used as transportation fuel and other chemicals [38][39].

While the gases produced from the pyrolysis process are mainly CO₂ (26.9%), CO (54.1%), H₂ (2.5%), and CH₄ (4.9%) [9]. It is different from syngas produced from gasification with the main characteristics including the higher gas CO₂, H₂ dan CH₄ [40][41].

4. Conclusion
In EFB pyrolysis, if the expected result is the maximum biochar yield, then the operation process is carried out at low temperature and heating. Meanwhile, if the expected maximum yield of bio-oil, then the operating process carried out is at a high temperature and heating rate. In EFB biochar with an optimum yield of 36.92% were produced at a temperature of 350°C, heating rate of 10°C / minute, with the particle size <2mm.

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