Combustion temperature analysis in a fluidized-bed reactor by utilizing palm oil biomass for a renewable energy

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Abstract. Biomass from palm oil is a renewable energy source that can be utilized and has very promising availability. Biomass energy is a renewable and sustainable energy that can replace conventional (fossil) fuels. The main objective of the experiment in this article is to analyze the combustion temperature, emissions, and efficiency of palm oil biomass fuel to use and applied in rural/remote areas. The palm oil biomass used in this study is palm kernel shells, empty fruit bunches, oil palm midrib, and oil palm fibers. The experiments in the research carried out in a fluidized-bed combustion chamber designed explicitly with capacities of up to 5 kg of biomass. The results of operations on fluidized-bed when the valve is open 100%, 75%, and 50% with overall palm oil biomass show a high combustion temperature. The highest combustion temperature was recorded in the TC test for 100% open valves with 3 kg biomass of 943 °C. While the minimum combustion temperature obtained on TF2 at 50% open valve with 1 kg biomass of 619 °C, overall combustion temperatures in this experiment showed high results. The maximum emission for O₂ is 20.4% which is obtained at 50% open valve, while for CO₂ the maximum emission is produced when 100% open valve is 19.9% with a biomass weight of 1 kg and 3 kg, respectively. The yield for maximum combustion efficiency when using 1 kg of biomass recorded at 50% open valve was 94.9%. While the minimum efficiency of 87.7% is obtained when the valve is 100% open with biomass of 2 kg. As the biomass fuel used in fluidized-bed increases, the combustion temperature also increases significantly.

1. Introduction
The climate that is increasingly erratic throughout the world today has triggered impacts on the environment. Most of these environmental impacts are caused by air pollution generated from fuel. Air pollution is a major environmental problem that poses various health risks for humans. These areas are
reported by the World Health Organization (WHO), where every year, outdoor air pollution and those caused by household appliances cause 7 million deaths shown in figure 1 [1, 2]. In recent decades, many researchers have researched in the field of renewable and sustainable energy intending to statement the problem of air pollution that continues to increase throughout the world. Renewable energy sources in Southeast Asia are currently abundant enough to be produced to replace conventional fuels [3–5]. This renewable energy source can be obtained very easily and cheaply, such as biomass from palm oil mills. Biomass from palm oil is a renewable energy that can use for electricity generation [6–11].

Indonesia and Malaysia are the most significant producing countries in supplying oil palm in the Southeast Asia region [12, 13]. The palm oil biomass can be presented as a power plant to replace conventional fuels. Power plants with biomass are also environmentally friendly if the management is appropriately done. Some researchers have previously conducted studies on palm oil biomass which use as a power plant [12–14]. The investigation and optimizing the process of electricity generation and heat by utilizing biomass waste in the palm oil industry has been carried out by [15]. In their research, they made three combinations of biomass, EFB, PKS, and Biogas with a preheater, which was used in the simulation. The results of the simulation of palm oil and biogas solid biomass waste from factory waste can provide sustainable and renewable fuels for palm oil production. Besides, the availability of additional electricity is possible because it is one of the best choices for the utilization of palm oil biomass waste. The investigation of various wastes used for electricity generation has also been studied comprehensively by [16]. Research to improve the physical and chemical properties originating from biomass and garbage to increase the thermal efficiency of power plants has been studied [17]. This biomass use to mix renewable energy in reducing dependence on fossil fuels, especially coal [17]. Sustainable energy supply from palm oil biomass such as empty fruit bunches, mesocarp fiber, oil palm shells, oil palm leaves, oil palm trunks obtained from oil palm plantations, and also wood biomass used as fuel have been investigated in Malaysia [18]. Palm oil biomass fuel can save energy up to 10 MW for biomass power plants. Based on the results of the analysis that generating 10 MW of biomass can reduce CO₂ emissions (50,130 t), SO₂ (750 t), NOx (218.65 t), and CO (22.83 t) in the environment compared to the energy mix. Evaluation of upstream and downstream oil palm farming activities is critical to carry out so that the goal of making palm oil waste a sustainable energy industry can achieve. The industrial roadmap representations and policies are designed to provide a unique improvement to the FiT system. Besides, the right strategies and frameworks can provide biomass as a sustainable energy industry [19, 20].
Indonesia has abundant biomass resources which are a source of renewable and cost-effective energy to be made as renewable and sustainable energy and environmentally friendly [21–23]. Forest biomass resources and from palm oil mills can be converted into bioenergy through various technologies which are one of the sources in Indonesia's energy mix in the future. In 2013 Indonesia produced biomass of around 50.4% of the remaining harvest and residual yields from wood processing reached 49.6% [22]. The amount of biomass found throughout Indonesia as a whole can contribute to the bioenergy potential of 87% of the total. Besides, there are three large islands in Indonesia, which provide 95% of the total bioenergy potential. The study of decentralized palm oil biomass gasification in Indonesia, which aims to reduce dependence on fossil fuel-based power plants in facilitating electrification in rural areas or remote islands has been studied [24]. Technically the palm oil biomass of gasification method also has been evaluated by reviewing various existing literature. Besides, proposals from two scenarios (V1 and V2, and M1 and M2) are each explicitly proposed for the use of power plants in villages and factories [24]. Indonesia has several regions and provinces that have a sufficient amount of biomass for the needs of biomass power plants.

One area that has the most palm oil biomass is the Sumatran region, specifically the Aceh Province. The city of oil palm plantations in Aceh in 2018 reached 26,660 hectares, with a production capacity volume of Certified Sustainable Palm Oil (CSPO) (RSPO certified sustainable palm oil) of 95,234 metric tons [25]. The amount of oil palm can produce palm oil mill waste that is large enough every year that can deliver into electricity generation. PKS with a capacity of 100 thousand tons of fresh fruit bunches annually can produce shells of around 6 thousand tons, fibers of 12 thousand tons, and empty fruit bunches of 23 thousand tons [26]. Whereas the generating efficiency of 25%, can generate electricity around each for the shells from 7.2 to 8.4 GW (e) h, fibers 9.2-15.9 GW (e) h, and 30 GW empty fruit bunches (e) h. With the availability of biomass, the biomass power plant from the palm oil mill can generate electricity around 1.4-1.6 GW (e) h if it is processed and produced correctly. However, the management of electricity from biomass in Aceh Province has not been adequately utilized. These are due to the lack of existing human resources and government policies on renewable energy not in favor of local investors and outside investors. Thus, to be able to utilize this abundant renewable energy source, it is very much needed support from various parties, especially from stakeholders or the government. With better support and policies, the development of renewable energy can be carried out well so that renewable energy can be applied as soon as possible, especially in remote/outermost regions [27, 28].

Power generation from biomass has been widely studied and applied in various countries in several applications both for industry and for domestic. Overall testing in several studies of biomass from palm oil mills for power plants shows promising results. The biomass power plant is renewable and sustainable energy because its availability in the plant is also very adequate to meet the energy in the future. The focus of this research is to apply and utilize renewable electricity generation energy from palm oil biomass for rural/remote areas in Aceh Province. Besides, analyses were also carried out on the temperature, emissions, and efficiency of the palm oil biomass combustion. This study, conducted experiments using four types of palm oil biomass such as empty fruit bunches (EFB), oil palm midrib (OPM), oil palm fiber (OPF), and palm kernel shell (PKS). This experiment was carried out in three stages, namely; the first stage is burning with 1 kg, 2 kg, and 3 kg of biomass. Each operation was carried out with 100% open valve, 75% and 50% with 4 different parameters.

2. Material and Setup
This study conducted experiments with biomass material from palm oil mills such as EFB, OPM, OPF, and PKS shown in figure 2. The biomass used in this experiment was 1 kg, 2 kg, and 3.5 kg, respectively. Each biomass material was treated four times with three different valve openings (50%, 75%, and 100%). While the chemical composition of each palm oil biomass is shown in table 1. Schematic diagrams in this experiment shown in figure 3. While the analysis tools used in this study include Thermocouple, Flue Gas DWYER 1207A, and Atomic Absorption Spectroscopy.
Figure 2. Material for palm oil biomass.

Table 1. Composition of palm oil biomass compounds [29].

| Categories      | EFB    | OPM    | PKS    | OPF    |
|-----------------|--------|--------|--------|--------|
| Carbon (C)      | 46.50% | 44.97% | 45.74% | 50.27% |
| Oxygen (O)      | 39.89% | 43.58% | 47.19% | 38.28% |
| Nitrogen (N)    | 0.89%  | 0.45%  | 0.25%  | 0.42%  |
| Hydrogen (H)    | 7.13%  | 6.99%  | 5.54%  | 7.07%  |
| Total Sulphur (S) | 0.21% | 0.14%  | 0.09%  | 0.63%  |
| Calorific Value (CV) | 4,469 Cal/gr | 4,278 Cal/gr | 4,515 Cal/gr | -      |
| Volatile Matter (VM) | 68.47% | 71.47% | 69.95% | 75.99% |
| Ash (A)         | 5.38%  | 3.87%  | 1.19%  | 5.33%  |

Figure 3. A fluidized-bed combustor (FBC) for biomass combustion.
3. Result and discussion

3.1. Profile of temperature

This study focuses on the burning characteristics of palm oil biomass in a fluidized-bed combustion chamber. Four types of biomass weighing 1 kg, 2 kg and 3 kg respectively tested on valves 50%, 75%, and 100% with four trials on each biomass used. The focus of this experiment is to analyze the combustion temperature, efficiency, O2, and CO2 coming out of the fluidized-bed combustion chamber. Airflow rates varying from 0.625, 0.9375, and 1.25 m³/s are used as variations of the combustion time. Temperature for four experiments when the valve opened 100% ranged from 722 °C to 943 °C. A series of tests and temperatures in four operations with 100% open valves and the use of biomass to investigate combustion behavior shown in Table 2.

Table 2. Operating conditions and combustion behavior of palm oil biomass at valve opening of 100%.

| Fuel Type | Total of using Biomass (kg) | Maximum of Temperature (°C) | Time of Burning (s) |
|-----------|-----------------------------|-----------------------------|---------------------|
| EFB       | 1                           | 893                         | 53                  |
|           | 2                           | 905                         | 42                  |
|           | 3                           | 943                         | 53                  |
|           | 1                           | 838                         | 66                  |
| OPM       | 2                           | 873                         | 40                  |
|           | 3                           | 830                         | 56                  |
|           | 1                           | 766                         | 52                  |
| PKS       | 2                           | 804                         | 40                  |
|           | 3                           | 808                         | 51                  |
|           | 1                           | 722                         | 49                  |
| OPF       | 2                           | 762                         | 38                  |
|           | 3                           | 851                         | 48                  |

Figure 4 (a) - (d) is a temperature profile shown from measurements taken from four experiments when the valve is open 100%, (a) temperature combustor (TC), (b) freeboard temperature 1 (TF1), (c) freeboard temperature 2 (TF2) and (c) freeboard temperature 3 (TF3). This observation was carried out for all four cases with similar biomass. The combustor temperature gradually decreased by 1 kg of biomass from the four trials conducted. As for biomass 2 kg and 3 kg at 200 seconds of combustion time until the end of combustion shows normal temperature. The best temperature produced 3 kg of biomass for all four trials with 100% open valve. The maximum temperature of the four tests with 100% open valve recorded at TC was 893 °C, 905 °C, and 943 °C for 1 kg, 2 kg, and 3 kg biomass, respectively. The minimum temperature recorded on TF3 is 722 °C and 762 °C. However, the 3 kg biomass at TF3 851 °C showed higher results than TF2 and TF1 for biomass 1 and 23 kg, which were 838 °C and 830 °C, respectively. The results of testing with biomass 1 kg, 2 kg, and 3 kg with four trials on open valves 100% higher than the results of tests conducted by [29]. The maximum temperature achieved in their study was between 650 °C and 680 °C with a burning time of 120 minutes. As for combustion in the test, they did use palm oil stone material in a pilot-scale bed reactor.

Subsequent experiments were carried out on 75% open valves with similar fuel in testing for 100% open valves. The results of trials conducted at this stage shown in Table 3. Figure 5 (a) - (d) shows the temperature profile from the measurement results with a 75% open valve in the fluidized-bed combustion chamber. This observation was carried out from the first to the fourth experiment with a time between 10 to 60 seconds. The 75% open valve shows that the temperature gradually decreases for all biomass used. These were very different in testing with 100% open valves. However, a more significant decrease was recorded in 1 kg biomass compared to 2 and 3 kg biomass at the same time. Besides, the time taken for the 75% valve is also longer than the test when the valve is 100% open.
The reduction in combustion temperature in this test arranged from 250 seconds to the end of combustion, while for the open valve 100% the decline began at 200 seconds until the end of burning for 1 kg of biomass. Maximum temperature in the experiment was recorded in biomass 2 kg and 3 kg of TC 899 °C and 878 °C, respectively.

Meanwhile, for 1 kg of biomass on TC, the temperature slightly decreased compared to 2 kg and 3 kg of biomass. The lowest maximum value for the four trials in 75% open valve recorded 1 kg of biomass for TF2 and TF3 of 685 °C and 689 °C, respectively. The results of testing by burning biomass 1 kg, 2 kg, and 3 kg at 75% open valve maximum temperature showed lower by 6 °C and 65 °C for biomass 2 and 3 kg at TC. The results shown in figure 4 are still higher than the results of tests conducted by [30]. The maximum temperature recorded in their trials between 650 °C and 680 °C with a burning time of 120 minutes.

Figure 4. Combustion temperature for different biomass at valve opening of 100% (4.a) Measurement point one (4.b) Measurement point two (4.c) Measurement point three (4.d) Measurement point four in the FBC.
Table 3. Operating conditions and combustion behavior of palm oil biomass at valve opening of 75%.

| Fuel Type | Total of using Biomass (kg) | Maximum of Temperature (°C) | Time of Burning (s) |
|-----------|-----------------------------|-----------------------------|---------------------|
|           | 1                           | 764                         | 74                  |
| EFB       | 2                           | 899                         | 50                  |
|           | 3                           | 878                         | 33                  |
|           | 1                           | 748                         | 52                  |
| OPM       | 2                           | 844                         | 49                  |
|           | 3                           | 844                         | 30                  |
|           | 1                           | 685                         | 51                  |
| PKS       | 2                           | 783                         | 46                  |
|           | 3                           | 784                         | 33                  |
|           | 1                           | 689                         | 69                  |
| OPF       | 2                           | 739                         | 49                  |
|           | 3                           | 741                         | 33                  |

Figure 5. Combustion temperature for different biomass at valve opening of 75% (5.a) Measurement point one (5.b) Measurement point two (5.c) Measurement point tree (5.d) Measurement point four in the FBC.
Table 4. Operating conditions and combustion behavior of palm oil biomass at valve opening of 50%.

| Fuel Type | Total of using Biomass (kg) | Maximum of Temperature (°C) | Time of Burning (s) |
|-----------|-----------------------------|-----------------------------|---------------------|
| EFB       | 1                           | 682                         | 44                  |
|           | 2                           | 840                         | 43                  |
|           | 3                           | 780                         | 48                  |
| OPM       | 2                           | 799                         | 44                  |
|           | 3                           | 738                         | 45                  |
|           | 1                           | 619                         | 40                  |
| PKS       | 2                           | 718                         | 40                  |
|           | 3                           | 680                         | 42                  |
|           | 1                           | 604                         | 39                  |
| OPF       | 2                           | 675                         | 38                  |
|           | 3                           | 665                         | 44                  |

Figure 6 (a) - (d) combustion temperature profile in a 50% open valve with similar biomass as 100% and 75% open valve. However, the combustion time carried out in this trial is longer than in the two previous tests. The combustion time on the valve opens 50% for 830 seconds compared to 570 and 600 seconds in the first and second tests. As in the first and second tests, in this experiment, the combustion temperature was analyzed based on the time and use of biomass 1 kg, 2 kg, and 3 kg. The highest temperature recorded on the 2 kg biomass for all experiments carried out with detailed results shown in figure 5. The maximum temperature for four experiments was found at 2 kg biomass with each of 840 °C (TC), 799 °C (TF1), 718 °C (TF2) and 675 °C (TF3). While the minimum temperature was recorded at 1 kg of biomass. The combustion temperature profile on the 50% open valve shows that biomass for 1 kg and 2 kg decreases gradually at an average time of 300 minutes compared to the 100% and 75% open valve. While 3 kg of biomass shows a better trend until the burning time is over. These show that the smaller the valve is open during combustion, the more time needed. Besides, the resulting temperature decreases compared to the wider open valve. The results of testing four experiments with similar biomass on the open valve 50% of the combustion temperature produced higher test results by [30]. While in their study, trials were carried out eight times compared to four experiments in this work. While a series of experimental results on 50% open valves with four experiments performed shown in table 4. Burning biomass in a fluidized bed to study the temperature and emissions of combustion has also been studied by several previous researchers [31, 32]. Their results show that NOx emissions were reduced by 30% and significant reductions were noted in CO emissions. However, their research combustion using biomass from non-wood like (straw, miscanthus, and peanuts).
3.2. **Gas emissions**

Unreacted O$_2$ concentrations show significant differences between 1 kg, 2 kg, and 3 kg palm oil biomass for 50%, 75%, and 100% open valves. The highest O$_2$ release recorded at 50% open valve is 20.4%, 20.3%, and 18.9% respectively shown in figure 7. While the lowest maximum value is observed at 2 kg of biomass at 100% open valve at 16.1%. Furthermore, followed by 3 kg of biomass on 75% 0.4% open valve and 0.7% for 50% open valve also obtained 3 kg of biomass. The experiments conducted in this article are part of a trial for electricity generation in rural/outside areas in Aceh Province. Where the design of tools made for this experiment can apply and utilize. A series of trial results show that the biomass power plant is very suitable for use in remote areas with adequate biomass availability. This biomass electricity is also beneficial to the environment and the cost required is not too expensive.

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**Figure 6.** Combustion temperature for different biomass at valve opening of 50% (6.a) Measurement point one (6.b) Measurement point two (6.c) Measurement point tree (6.d) Measurement point four in the FBC.

**Figure 7.** O$_2$ emissions for different valve opening and materials of biomass.
Figure 8 is the CO₂ emissions from the combustion analysis results with biomass from a coconut factory tested with three trials and three different types of biomass. CO₂ emissions show a significant reduction at 4 and 5 minutes. However, the difference indicated for 3 kg biomass at 50% open valve. The results obtained increased significantly from the beginning to the end of combustion compared with biomass 1 kg and 2 kg. The minimum value of CO₂ from the three parameters with different biomass recorded in the starting valve 100% for biomass 1 kg and biomass 1 kg and 2 kg respectively 2.9% for 75% open valve. Whereas the maximum CO₂ emissions for the three parameters found at 3 kg of biomass 19.9% in the 100% open valve compared to the biomass and other open valves in this test.

![Figure 8. CO₂ emissions for different valve opening and materials of biomass.](image)

3.3. Combustion efficiency

Finally, the analysis in this experiment carried out on the efficiency of combustion of biomass in open valves 100%, 75%, and 50%. Where the results of combustion efficiency in this test, as shown in figure 9. The maximum combustion efficiency in this trial was recorded at 1 kg biomass for 50% open valve compared to 100% 91.7% open valve and 75% for 94.5% for 3 kg biomass. Combustion efficiency shows results following the temperature of the burner. Where the increased combustion temperature shows better efficiency, as shown in figure 8.

![Figure 9. Efficiency for different valve opening and materials of biomass.](image)

3.4. Ash Deposit

Ash deposit is the residual ash from the burning of palm oil biomass contained in this study is a mixture of EFB, OPM, PKS, and OPF. Ash deposit generated in this study taken in the combustor
fluidized-bed combustor. The burning ash of palm oil biomass is one of the biomasses from the plantation sector with an abundant amount. This palm oil waste can be obtained at a little cost in a sustainable and environmentally friendly manner. Oil palm waste has been thrown away for nothing and without proper management so that its existence has caused various environmental problems and endangered human health risks [33]. The ash deposit investigation aims to determine the composition of chemical compounds found in the residual combustion of palm oil biomass and then compared them with chemical compounds in ash from the burning of coal biomass. The structure of the ash deposit chemical compounds from burning palm oil biomass in this study is shown in table 5.

| No | Chemical Compounds | Total | Unit |
|----|--------------------|-------|------|
| 1  | Al₂SO₃             | 4,710 | %    |
| 2  | SiO₂               | 30,860| %    |
| 3  | K₂O                | 1,910 | %    |
| 4  | MgO                | 2,54  | %    |
| 5  | CaO                | 10,55 | %    |
| 6  | Iron (Fe)          | 0,63  | %    |
| 7  | Natrium (Na)       | 0,11  | %    |
| 8  | Cadmium (Cd)       | <0,0004 mg/kg |
| 9  | Copper (Cu)        | 151,5964 mg/kg |
| 10 | Nickel (Ni)        | 15,1967 mg/kg |

The combustion results of palm biomass contain enough chemical compounds that can use for various other functions. One of them is as an inexpensive alternative fertilizer, this is because the ash from the burning of palm oil biomass contains nutrients needed by plants such as K, Ca, and Mg [33]. The ash deposit composition obtained from palm oil biomass contained in chemical compounds is similar to the results of coal combustion. The utilization of the content used as a parameter for additives in mixing for the manufacture of concrete such as SiO₂ content. The ash results from burning palm oil biomass. The SiO₂ content contained in coal reaches 30-50%. The residual ash from the combustion of palm oil biomass produced in this study contained 30.86% SiO₂. This content can use as a mixture for making concrete because SiO₂ contained in the ash from the burning of palm oil biomass is the primary raw material for cement [34]. Besides, ash from the burning of palm oil biomass can use as an air filter in motor vehicles. Because with this ash content of palm oil biomass can save fuel consumption up to 10% [36]. Combustion ash from palm oil biomass can also use as an additional composition for the manufacture of polystyrene polymers. This is because it has better power than polystyrene in general [33]. Besides, the ash from combustion can also be used as a mixture in the mortar (cement, sand, and water) to strengthen the compressed concrete [37].

4. Conclusion
The thermochemical characteristics of biomass fuels from oil palm mills were evaluated using a fluidized bed combined with various testing parameters, including the effects of temperature, emissions, and combustion efficiency. The main experimental results from this study are Combustion of palm oil biomass in a variety of open valves against the effects of temperature, emissions and combustion efficiency in fluidized-bed has been successfully carried out. The combustion temperature for all types of biomass used decreases when the valve is open 50% and vice versa has an increase in the 100% open valve. The maximum O₂ emission gas measured in this study reached 19.9% at 3 kg biomass for 100% open valves while the value of the minimum O₂ emissions gas recorded at 1 kg of biomass 2.9% for 100% open valves and biomass 1 and 2 kilograms of 75% open valves respectively at 2.9%. The maximum CO₂ emissions were recorded at 1 kg of biomass for 50% open valves by 94.9% and a minimum of 87.7% for 2 kg of biomass at 100% open valves. Combustion temperature
maximum found in 3 kg biomass for open valves 100% 943 °C, while the minimum combustion temperature of 604 °C on the open valve is 50% for 1 kg of biomass.

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