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Optimal Composition of Palm Oil Biomass to Minimize Biomass Power Plants' Greenhouse Gases Emission

The increasing energy demand and rising concern about climate change have become two significant factors in finding alternative energy sources other than fossil fuels. Biomass has been implemented by several tropical countries such as Indonesia and Malaysia to answer this challenge by utilizing palm oil by-products as boiler fuels to generate steam for palm oil mill (POM) processing as well as for electricity generation. Fiber and kernel shell have become two major palm oil residues that have been implemented for this purpose. Moreover, empty fruit bunch (EFB) can also become another alternative biomass to fuel the boiler. This study is aimed at analyzing and optimizing the utilization of fiber, shell, and EFB by adjusting percentile contents of those three constituents and evaluating the CO_2 production. The result of this analysis indicates that the best composition to minimize the CO_2 of the biomass power plant is using 70% fiber, 0% shell, and 30% EFB. However, the increase of NO_2 and SO_2 must also be considered to find the correct balance between those three emissions. In addition, EFB should be pretreated (drying and shredding) before the combustion to reduce the water content and the dimension of EFB.

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Keywords: biomass, palm oil by-products, fiber and Kernel shell, empty fruit bunch (EFB), minimal emission, alternative energy sources, biomass conversion

1 Introduction

Fossil fuels including oil, coal, and natural gas are currently the main sources of energy in the world. However, it is projected that these energy sources would run out in the following 40–50 years [1]. Additionally, the world is trying to reduce carbon emissions by 80% and switch to using a variety of renewable energy resources (RES) that are less environmentally harmful such as solar, wind, biomass, and others in a sustainable way. These RES are less likely to cause environmental harms like global warming, acid rain, and urban smog. Biomass as one of the RES is the earliest sources of energy with very specific properties [2]. Palm oil industry as the greatest biomass producer has significantly increased in recent years, especially in tropical regions. Indonesia and Malaysia are located in tropical regions that had palm oil plantations area of 16,472,000 ha (77.5% of the total plantations area in the world) in 2014. The remaining 720,000 ha is in Thailand, 440,000 ha in Nigeria, 354,000 ha in Colombia, and 2,188,000 ha in other countries [3]. Crude palm oil (CPO) and palm kernel oil (PKO) are the main products in the palm oil industry. Originally, the CPO was used for the food industry, but now, due to the high energy demand, the CPO is utilized for biodiesel fuel and oleo-chemical production [4].

Besides CPO and PKO, palm oil production creates massive biomass residue. Around 87 million tons/year of wet basis biomass residues were produced in 2010. The forms of biomass residues are empty fruit bunches (EFBs), as a result of fruit removal; mesocarp fiber, produced after fruit pressing; palm kernel shells (PKS) as a result of nuts; ash as by-products of burning the fiber and palm kernel shell; sludge as a result from the anaerobic lagoon after water treatment; and trunk, roots, and leaves as a result of plantation residue [5]. Although many residues are produced during the oil palm activities, only three of them are commonly utilized for the boiler's combustion process: EFB, fiber, and PKS. Almost all palm oil industry produces their electric power by using biomass as boiler fuel through the combustion process in the furnace. Still, at the same time, using this biomass in the combustion process will release greenhouse gases (GHGs) into the atmosphere [6].

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The increase of GHG in the atmosphere becomes a major concern of climate issues at the same time. The increase in GHG results in higher average temperatures and dramatic climate change phenomena [7]. Therefore, palm oil biomass combustion, as one of the contributors to the increase of GHG, needs to be treated to create more clean and sustainable energy. For that purpose, developing biomass combustion processes such as adjusting biomass composition for boiler fuel to obtain the most minimum greenhouse gas emission is the right solution to be proposed.

2 Palm Oil Mill Process

Most palm oil plants in Indonesia and Malaysia utilize small boilers for electricity. The type of boiler is usually an open D-type water tube boiler. It can utilize any kind of fuel by making a small modification. The capacity of this boiler is 30–60 tons fresh fruit bunch (FFB) per hour. In the next section, the typical palm oil mill (POM) process will be explained [8].

2.1 Sterilization. Sterilization is the process of palm fruit cooking before being digested and pressed, usually using steam above atmospheric pressure [9]. This process avoids rising free fatty acid (FFA) during the pulping process. When fruit bunches are taken from trees, and kept for a few days, much of the fruit will be loose from the bunches. When the fruits were pounded and pressed, oil with a very high FFA would be produced. Fat-splitting chemicals would stay active and hydrolyze the oil when the fruit is pulped within the mortar. So, sterilization is required to avoid the rising of this FFA [10].

2.2 Threshing. During the threshing process, sterilized fruits will be segregated from the sterilized fruit bunch [11]. In this station, the EFB as one of biomass materials is obtained.

2.3 Digestion. To guarantee that the fruits are smooth for pressing when transported to the press station, the fruits are blended with steam to mesh the fruit in the digester. Fruit is meshed by a blade that spins inside the digester while it is running. In the digester, steam is used to assist the meshing process [12].

2.4 Oil Extraction. After digestion, the next process is oil extraction. It is done by pressing digested palm fruit using a screw-type press machine [13].

2.5 Clarification (Purification). After extraction, the oil usually contains certain amounts of impurities in water consisting of vegetable matter. It can be in the form of insoluble solids, some of which are dissolved in the water. Removing the water contained in crude palm oil can be done by settling or centrifuging. However, a small proportion of it is dissolved in the oil. It can only be removed by a dehydrator with or without a vacuum [14].

2.6 Nut/Fiber Separation. A cake made of nuts and fiber is produced during the extraction. The composition of this cake varies, depending on the fruit type. Before being fed into the nut/fiber separator, preliminary breaking treatment is required. It will lead to separation by mechanical means or by using an air stream [15].

2.7 Kernel Extraction and Drying. After the fiber is separated from the nuts, the latter is ready for cracking. Any uncracked nuts must be removed and recycled, and the shell must be separated from the kernels. Before being packed, the kernels must be dried and cleaned [16].

Whole production process and the product of palm oil are shown in Fig. 1.

3 Palm Oil Biomass

Palm oil is the biggest source of edible oil in the world. In 2011, Indonesia produced about 23 MT crude CPO or produced 46% of the total palm oil worldwide [17]. Due to the growth of the population and the need for food, chemical industry, and energy, palm oil production will remain increasing. The more CPO is produced; the more palm biomass is wasted. Based on its capacity, the composition of palm oil residues is around 12–15% fiber, 5–7% shell, and 20–23% EFB [18].

Palm biomass has been used as a renewable energy source since long ago, but its utility is still not popular. The Indonesian government released the National Energy Policy in 2006, which aimed to increase biomass utilization by 5% in 2025. A cogeneration system consisting of a boiler, turbine, and generator is applied to produce steam and electricity in the milling process [19]. Fiber and shell with 70:30 composition is the most common biomass fuel that is burnt directly in a boiler to form saturated or superheated steam [20]. Half of the steam is used for milling processes, while the rest is converted to electricity by using a turbine. EFB is not commonly used for fuel because it contains high moisture. However, like fiber and shell, EFB also has a high caloric value that can be utilized as energy source. Therefore, in this term project, the EFB will be considered as fed fuel along with fiber and shell. The subject of this study will be based on a palm oil manufacturer with a production capacity of 30 tones/h in Sei Mangkei Palm Oil Mill in North Sumatera, Indonesia. The mass balance of the 30 tones/h palm oil production is shown in Fig. 2.

4 Pretreatment Process of Empty Fruit Bunch

EFB contains 65% of water after sterilizing and threshing process [21]. When the water concentration of a fuel increases, the temperature inside the combustion chamber will decrease, which indicates low combustion efficiency of the boiler. On the other hand, the physical form of EFB is also relatively big to be added as boiler fuel. That physical form complicates the combustion process because they have varying shapes, densities, and hardness. So, it is required to be shredded as the first step of treating the EFB as boiler fuel. A technology to decrease EFB water content that can improve the quality of empty fruit bunches is currently being developed, which is hydrothermal treatment (HT). HT is known as a method to convert solid waste or biomass, which has high water content into dry, uniform, and powdery forms. In addition, HT can also remove inorganic components like Ca, S, P, Mg, K, Fe, and Mn from the biomass. Hydrothermal is often called the torrefaction process. Torrefaction is a thermal treatment of biomass in the absence of oxygen for approximately 15–60 min at a temperature of 200 °C—300 °C and atmospheric pressure. Heat treatment changes not only the fiber structure but also the ductility of the biomass. During the torrefaction process, the biomass will experience devolatilization, which led to decrease in weight, but the initial energy content of the biomass that has been undergoing torrefaction is maintained in the solid product so that the energy density of biomass becomes higher than the initial biomass. The combination of the EFB pretreatments starting from shredding to hydrothermal treatment deserves to be implemented to maximize EFB effectiveness in terms of improving the physical and chemical properties of EFB as boiler fuel [22].

5 Combustion of Palm Oil Biomass

The combustion process of biomass will produce CO and CO_2 as a result of a carbon reaction, and oxygen will leave material in the form of ash. Biomass has a lower heating value of about 15–20 MJ/kg compared with coal 25–33 MJ/kg. This means that for every

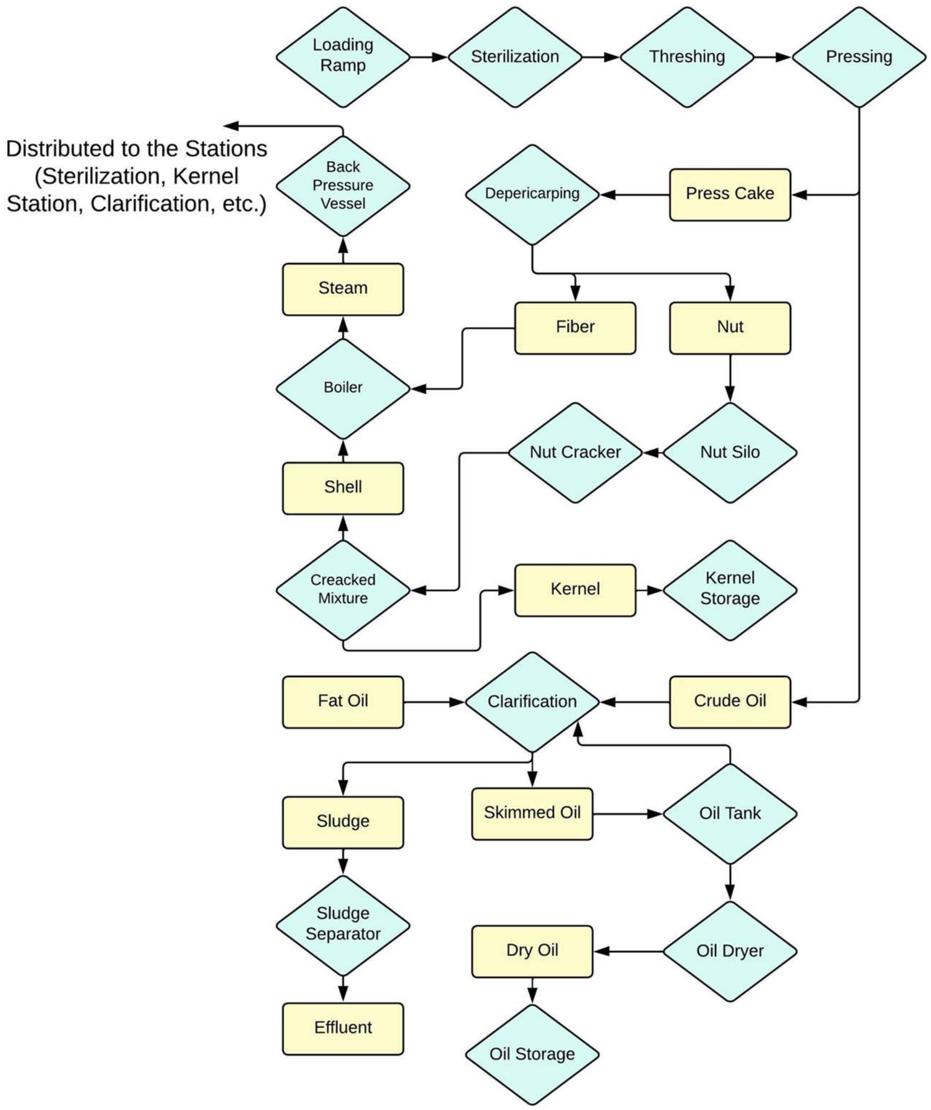

Fig. 1 Operating process and product of palm oil mill

kilogram of biomass, it can only produce 2/3 of the energy of 1 kg of coal [23]. In the palm oil manufacturing process, the three kinds of solid biomass contain different chemical components (Table 1).

The chemical components of the solid biomass will release gas emissions into the atmosphere after the combustion process in the chamber. The gas emission analysis, especially for carbon, will be explained along with the fuel composition analysis to obtain the most minimum emission released by the fuel combustion process [27].

6 Problem Statement

EFB biomass is rarely used by the industry as a boiler fuel due to its moisture content, even though the availability of EFB as waste product is abundant, and it is usually used for soil fertilization or simply discharged without any further treatment [28]. This study analyzed the possibility of EFB utilization mixing with fiber and shell, by using variation of the composition method. This method evaluated the composition of these three components (EFB, fiber, and shell) to find the best fuel performance and to reduce exhaust gas emission. Boiler data performance in palm oil manufacturer with a production capacity of 30 tons/h in Sei Mangkei Palm Oil Mill in North Sumatera, Indonesia, is used to analyze and calculate mass balance, energy content, and released emission. Fuel composition variation is adjusted to calculate emission from the fuel combination to achieve the most minimum GHG emission from the biomass utilization.

7 Methodology

In order to investigate the most minimum greenhouse gas emission from the combustion of biomass, we developed an analysis of biomass combustion by using ultimate analysis (Table 1) with the methodology as follows.

7.1 Data Source

Obtaining Mass Balance of Palm Oil Production Process. Material mass balance analysis is very important in oil palm processing because it provides a means of quantifying the expected wastes from the process and making provisions for their utilization to avoid environmental impacts [29]. The mass balance of the palm oil process is shown in Fig. 2 with solid waste (biomass) as the concern. During palm oil processing, a palm oil mill with 30 tones/h capacity can convert FFB into solid waste with 22.49% EFB, 10.62% fibers, and 5.2% shell.

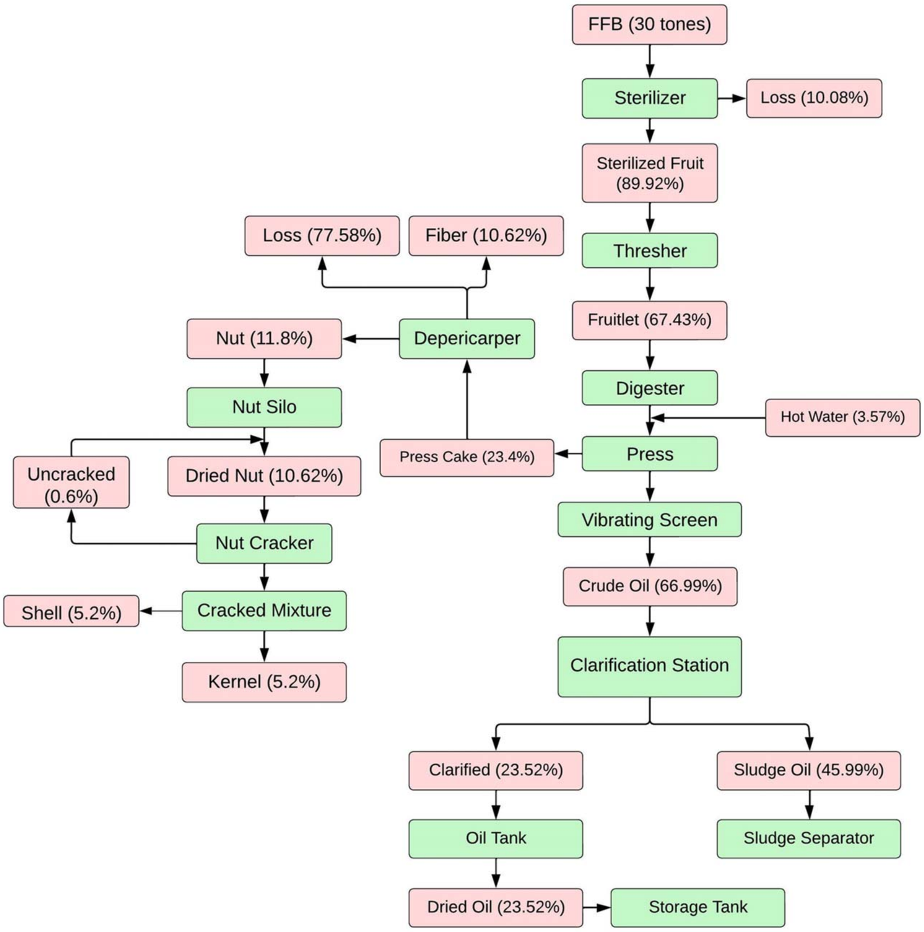

Fig. 2 Mass balance of palm oil process

Table 1 Characteristics of the main components of solid biomass exiting the palm oil mill [24–26]

	Proximate analysis		
(% mass)	Fiber	Shell	EFB
FC	48.61	68.2	8.36
VM	13.2	16.3	79.34
Moisture (M)	31.84	12	7.8
Ash (A)	6.35	3.5	4.5
	Ultimate analysis		
Carbon, C	47.2	52.4	43.52
Hydrogen (H_2)	6	6.3	5.72
Sulphur (S)	0.3	0.2	0.66
Oxygen (O_2)	36.7	37.3	48.9
Nitrogen (N_2)	1.4	0.6	1.2
	Heating value		
Higher heating value (MJ/kg)	19.06	20.09	18.8

Proximate Analysis, Ultimate Analysis, and Energy Contained of Biomass. Biomass fuels are characterized by what is called the "proximate and ultimate analysis." The proximate analysis typically involves determination of moisture, volatile matter, fixed carbon, and ash, and represents the most frequently used method for biofuel characterization. The ultimate analysis gives the elemental (C, H, O, S, and N) analysis based on those elemental reactions to the supplied oxygen [30]. Carbon, nitrogen, sulfur, and oxygen are the main components of palm oil biomass. Those elements and oxygen react during combustion in an exothermic reaction, generating CO_2, NO_2, and SO_2. Thus, they contribute in a negative way to the environment, which is becoming our concern to make this study.

7.2 Data Analysis. The analysis of biomass combustion was performed in numerical analysis. Knowing required heat of the boiler is necessary as the first step in this study. It has a purpose to obtain the amount of biomass supplied to the combustion chamber of the boiler by dividing the heat requirement value with the energy contained in biomass. The calculation will be made based on boiler data and Rankine cycle analysis. Then, the required air (included 20% of excess air) to burn each constituent (EFB, fibers, and shells) will be calculated. In this study, variations of biomass composition are considered in terms of obtaining the most minimum greenhouse gas emission from the combustion of biomass through the ultimate analysis method. Then, recommendation and improvement for the combustion process or biomass power plant need to be suggested for a better study in the future.

8 Results and Discussion

8.1 Boiler Fuel Requirements. The following calculation is based on a subject of study of palm oil mills with a capacity of 30 tons FFB per hour. Fiber, shell, and EFB will be considered as fuel. EFB must be shredded and dehydrated for easy combustion. However, this will increase the cost of pretreatment. So, in this

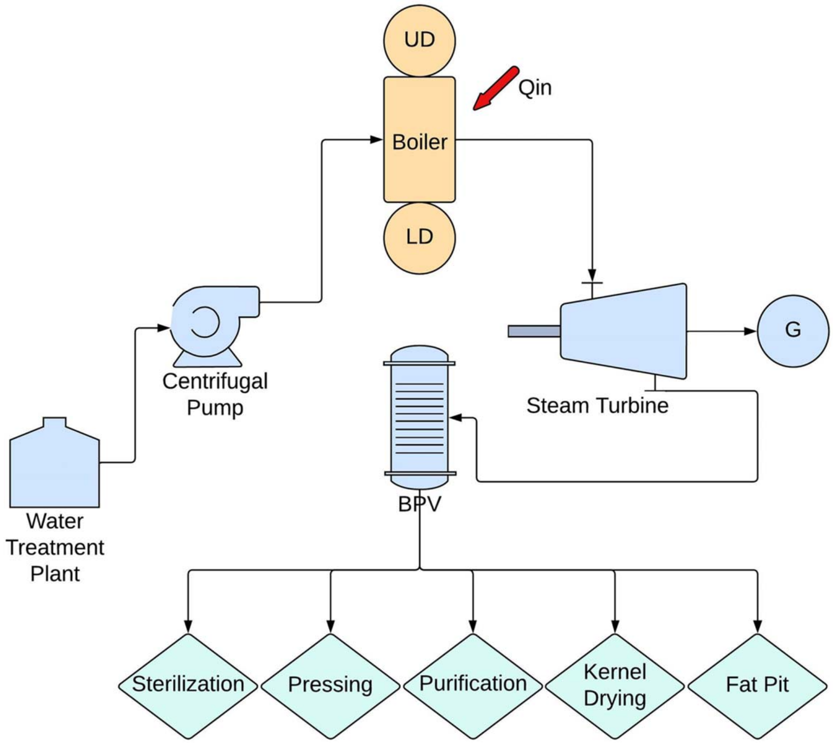

Fig. 3 Rankine cycle analysis schematic of biomass power plant

term project, EFB will be included as boiler fuel along with fiber and shell without pretreatment.

The boiler's steam arises because the water phase changes (liquid) to vapor. Heat energy is needed for the boiling process, which is obtained from burning fiber, shell, and EFB. Sei Mangkei Palm Oil Mill in North Sumatera as one of the palm oil manufacturers has a production capacity of 30 tons/h. The installed boiler is Water Tube Takuma Boiler N1200R with maximum pressure work 20 kg/cm^2, working pressure 18 kg/cm^2, and maximum steam evaporation 23 tons/h [31]. Figure 3 shows the Rankine cycle scheme of the biomass power plant and the distribution of the turbine waste steam.

To calculate the boiler's fuel requirement, first, the heat requirements required by the boiler are presented using the following formula [32]:

$$Q = \dot{m} c_P \Delta T = \dot{m}\,(h_3 - h_2) \tag{1}$$

where Q = heat requirement (kJ/s), c_P = specific heat (kJ/kg K), ΔT = temperature difference (K), and $h_3 - h_2$ = enthalpy difference (kJ/kg).

The calculation is made from boiler data and Rankine cycle analysis in the form of steam mass flowrate, pressure, feed water pressure, exhaust steam pressure, and electric power generated. The complete calculation is presented in Appendix A, and the summary of the calculation is shown in Table 2.

Table 2 Parameters of biomass power plant in Sei Mangkei POM

Parameters	Value
Mass flow of water	23,000 kg/h
The pressure of feed water	101.325 kPa
Superheated pressure	1800 kPa
Superheated temperature	225 °C
Steam pressure output (turbine)	325 kPa
Electricity output	2.02 MW
Heat Requirement	15,501.8 kJ/s

On the basis of heat requirement of the power plant system to generate 2.02 MW electricity output, we can determine the amount of fuel mass needed by the boiler regarding the heating value of the biomass fuel. It is shown in Table 3.

8.2 Air for Combustion Requirements. Combustion is a reaction between oxygen and fuel, which generates heat. The most elements contained in the fuel are carbon, hydrogen, and a small amount of sulfur. The combustion of biomass in boilers is a reaction between oxygen and fuel in the form of shells, fibers, and EFB. Oxygen is taken from the air composed of 21% oxygen and 78% nitrogen (volume percentage). So, we need to calculate the air requirement (theoretical air + excess air) for the combustion process using the following equation. However, in actual combustion, complete combustion cannot occur by relying only on

Table 3 Fuel requirement of biomass power plant system for production capacity 30 tons/h

Heat requirement	Higher heating value of biomass (MJ/kg)	Mass of biomass (kg/s)
15.5 MJ/s	19.06 (fiber)	0.81
	20.09 (shell)	0.77
	18.8 (EFB)	0.82

Table 4 Theoretical and excess air for perfect combustion

Biomass	Theoretical air (kg air/kg fuel)	Theoretical + excess air 20% (kg air/kg fuel)
Fiber	6.12	7.344
Shell	6.72	8.064
EFB	5.05	5.05

Table 5 The relation of fuel composition with required air

%	Comp. 1	Comp. 2	Comp. 3	Comp. 4	Comp. 5	Comp. 6	Comp. 7	Comp. 8
Fiber	70	60	70	60	50	50	70	70
Shell	30	40	20	20	30	20	10	0
EFB	0	0	10	20	20	30	20	30
Mass flow of each constituent to satisfy required heat of the boiler (kg/s)								
Fiber	0.567	0.486	0.567	0.486	0.405	0.405	0.567	0.567
Shell	0.231	0.308	0.154	0.154	0.231	0.154	0.077	0
EFB	0	0	0.082	0.164	0.164	0.246	0.164	0.246
Required air (included 20% excess air) to burn each constituent (kg/s)								
Fiber	4.16	3.569	4.16	3.569	2.97	2.97	4.16	4.16
Shell	1.86	2.48	1.24	1.24	1.862	1.241	0.62	0
EFB	0	0	0.41	0.828	0.828	1.24	0.828	1.24

Table 6 Emissions gas produced by biomass power plant

%	Comp. 1	Comp. 2	Comp. 3	Comp. 4	Comp. 5	Comp. 6	Comp. 7	Comp. 8
Fiber	70	60	70	60	50	50	70	70
Shell	30	40	20	20	30	20	10	0
EFB	0	0	10	20	20	30	20	30
Total GHG emission of the composition (kg/s)								
CO_2	1.426	1.434	1.409	1.399	1.4077	1.3906	1.3922	1.375
NO_2	0.0043	0.00415	0.0051	0.0057	0.00552	0.0063	0.0059	0.00665
SO_2	0.0307	0.0285	0.0324	0.0319	0.0297	0.0314	0.0341	0.03582
Total GHG emission of the composition per year ($\times 10^6$ kg/year)								
CO_2	44.98	45.23	44.44	44.15	44.39	43.854	43.90	43.36
NO_2	0.136	0.1308	0.161	0.180	0.174	0.1984	0.185	0.209
SO_2	0.967	0.898	1.021	1.006	0.936	0.990	1.075	1.130

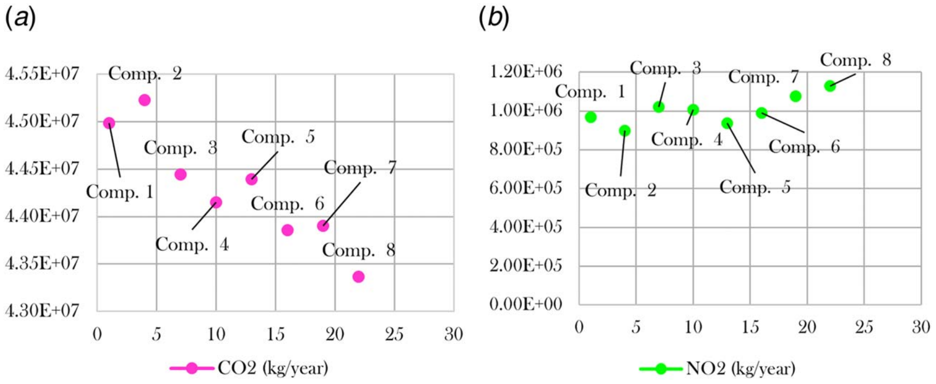

Fig. 4 (*a*) CO_2 and (*b*) NO_2 produced by biomass power plant (kg/year)

theoretical air requirements. For this reason, excess air is needed so that combustion can occur close to perfect conditions. In the beginning, we try to classify the combustion process consisting of four functions [20]:

$$C + O_2 \rightarrow CO_2 + \text{Heat}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{Heat}$$

$$S + O_2 \rightarrow SO_2 + \text{Heat}$$

$$N + O_2 \rightarrow NO_2 + \text{Heat}$$

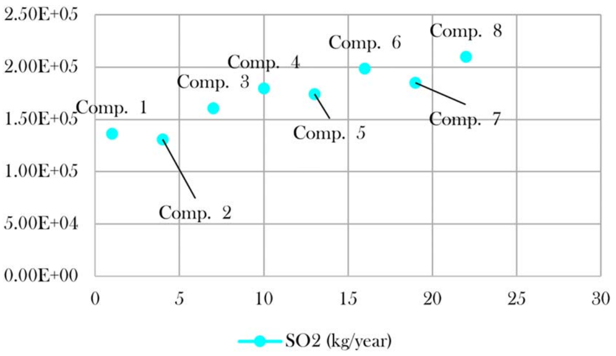

Fig. 5 SO_2 produced by biomass power plant (kg/year)

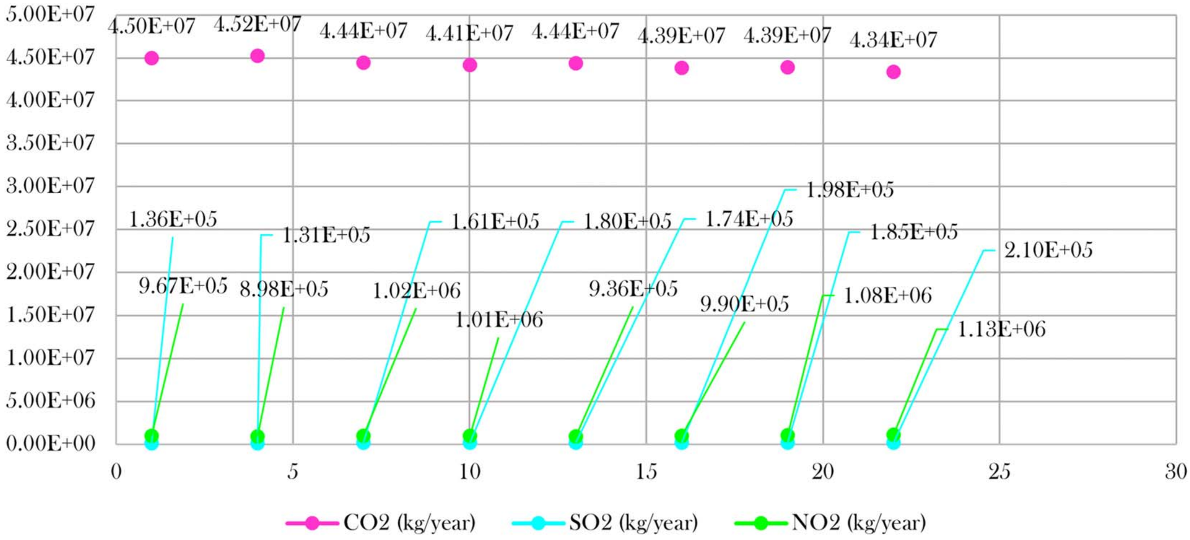

Fig. 6 Total GHG produced by biomass power plant (kg/year)

Table 7 Effect of NO_2 and SO_2 gases [36]

Effect of nitrogen dioxide (NO_2)	Effect of sulfur dioxide (SO_2)
Contributes to death and serious respiratory illness (e.g., asthma, chronic bronchitis) due to fine particles and ozone.	Contributes to death and serious respiratory illness (e.g., asthma, chronic bronchitis) due to fine particles.
Acidifies surface water, reducing biodiversity, and killing fish.	Acidifies surface water, reducing biodiversity, and killing fish.
Damages forests through direct impacts on leaves and needles, and by soil acidification and depletion of soil nutrients.	Damages forests through direct impacts on leaves and needles, and by soil acidification and depletion of soil nutrients.
Damages forest ecosystems, trees, ornamental plants, and crops through ozone formation.	Contributes to decreased visibility.
Contributes to coastal eutrophication, killing fish and shellfish	Speeds weathering of monuments, buildings, and other stone and metal structures.
Contributes to decreased visibility (regional haze).	–
Speeds weathering of monuments, buildings, and other stone and metal structures.	–

The aforementioned four compounds are mentioned as a combustion product. If the composition of the fuel is known, we can calculate the proportional air required with the fuel to reach perfect combustion.

Perfect combustion of carbon will form CO_2 with equation:

$$C + O_2 \rightarrow CO_2$$

$$12\,\text{kg C} + 32\,\text{kg } O_2 \rightarrow 44\,\text{kg } CO_2$$

$$1\,\text{kg C} + 2.67\,\text{kg } O_2 \rightarrow 3.67\,\text{kg } CO_2$$

Perfect combustion of hydrogen will form H_2O with equation:

$$4H + O_2 \rightarrow 2H_2O$$

$$4\,\text{kg H} + 32\,\text{kg } O_2 \rightarrow 36\,\text{kg } H_2O$$

$$1\,\text{kg H} + 8\,\text{kg } O_2 \rightarrow 9\,\text{kg } H_2O$$

Perfect combustion of sulfur will form SO_2 with equation:

$$S + O_2 \rightarrow SO_2$$

$$32\,\text{kg S} + 32\,\text{kg } O_2 \rightarrow 64\,\text{kg } SO_2$$

$$1\,\text{kg S} + 1\,\text{kg } O_2 \rightarrow 2\,\text{kg } SO_2$$

Perfect combustion of nitrogen will form NO_2 with equation:

$$N + O_2 \rightarrow NO_2$$

$$14\,\text{kg N} + 32\,\text{kg } O_2 \rightarrow 46\,\text{kg } NO_2$$

$$1\,\text{kg N} + 2.29\,\text{kg } O_2 \rightarrow 3.29\,\text{kg } NO_2$$

Meanwhile, 1 kg of air contains 0.23 kg of O_2, so that required theoretical air is calculated as follows [33]:

$$\text{Theoretical air}\left(\frac{\text{kg air}}{\text{kg fuel}}\right) = \frac{[(2.67 \times \%C) + (8 \times \%H_2) + (\%S) + (2.29 \times \%N_2) - (\%O_2)]}{0.23}$$

$$\text{Perfect combustion (adding 20\%, 30\%, or 50\% excess air)} = \text{Theoretical air} \times (1.2, 1.3, \text{ or } 1.5)$$

The complete theoretical air calculation is presented in Appendix B, and the summary is shown in Table 4.

8.3 Emissions of Biomass Combustion. Emissions generated during the combustion process of fiber, shell, and EFB are strongly influenced by the fuel composition and excess air. From processing 30 tons/h of FFB, the Sei Mangkei mill can produce 1.6 kg/s of fiber, 0.69 kg/s of shell, and 1.83 kg/s of EFB. However, to reach 15.5 MJ/s supplied heat to the boiler, the maximum limit of the biomass fuel should not be higher than the stated value in

Table 3. The relation between fuel composition and air with POM production capacity of 30 tons/h is shown in Table 5.

Based on the mass flow of the biomass and the airflow data, we can calculate the GHG emission produced by the combustion process shown in Table 6.

According to Table 6, it can be concluded that composition 8 produces the least CO_2 (43 × 106 kg/year). However, composition eight also simultaneously produces the highest NO_2 (0.21 × 106 kg/year) and SO_2 (1.13 × 106 kg/year), which can cause other environmental issues. The plots of CO_2, NO_2, and SO_2 emissions produced based on the biomass composition are shown in Figs. 4 and 5.

The combination of those graphs is shown in Fig. 6.

If we are focusing on the total GHG emissions, composition 8 is the best option to be applied. However, we want to put the concern on the hazardous level of the gas emission. NO_2 and SO_2 gases have more impact to harm human life and the environment. NO_2 with high doses and prolonged exposure can irritate the mucus, sinuses, and pharynx, causing irregular respiration and even pulmonary edema [34]. On the other hand, the SO_2 gas has the characteristic of being colorless and has a sharp odor. Furthermore, SO_2 can cause acid rain when it reacts with water vapor and produces H_2SO_4 [35]. The other impact of NO_2 and SO_2 occurs when they are emitted into the atmosphere, and those gases undergo chemical reactions to form compounds that can travel long distances. These chemical compounds take the form of tiny solid particles or liquid droplets and can remain in the air for days or even years [36]. The more specific effect of NO_2 and SO_2 on the Health and Safety Environment has been stated in Table 7.

Based on the combustion analysis, composition 2 of biomass produces the least NO_2 (0.1308×10^6 kg/year) and SO_2 (0.898×10^6 kg/year). Considering that impact of NO_2 and SO_2 is more dangerous to health, safety, and environment (HSE), the fuel composition 2 (Fiber 60%, shell 40%, EFB 0%) is considered to be implemented in palm oil biomass power plant.

9 Conclusions

The fuel composition has an essential role in deciding the emission gas concentration produced by the biomass power plant. Almost all biomass power plants in Indonesia or Malaysia implement composition 1 (fiber 70% and shell 30%). However, the emission gas produced by composition 1 has shown a negative impact in resulting CO_2. It will produce 44.98×10^6 kg/year of CO_2, 0.136×10^6 kg/year of NO_2, and 0.967×10^6 kg/year of SO_2, which show relatively high emissions. Therefore, it needs to be improved by implementing composition 8 to reach the minimum total GHG emission produced by biomass power plants. In addition, the EFB in composition 8 must be pretreated before it is combusted to reduce the water content and the dimension of EFB. In another case, if HSE becomes a concern, reducing NO_2 and SO_2 should be prioritized by implementing composition 2 of biomass in the palm oil biomass power plant.

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Conflict of Interest

There are no conflicts of interest. This article does not include research in which human participants were involved. Informed consent not applicable. This article does not include any research in which animal participants were involved.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

Nomenclature

A = ash
CPO = crude palm oil
EFB = empty fruit bunch
FC = fixed carbon
FFA = free fatty acid
FFB = fresh fruit bunch
GHG = greenhouse gas
HT = hydrothermal
HSE = health, safety, and environment
M = moisture
PKO = palm kernel oil
PKS = palm kernel shell
POM = palm oil mill
RES = renewable energy resources
VM = volatile matters

Appendix A: Rankine Cycle Analysis of Biomass Power Plant

State 1

$$P_1 = 1 \text{ atm} = 101.325 \text{ kPa} \rightarrow v_F = 0.001043 \text{ m}^3/\text{kg}$$
$$h_1 = 419.06 \text{ kJ/kg}$$

State 2

$$P_2 = 1800 \text{ kPa} \rightarrow w_P = h_2 - h_1 \rightarrow h_2 = w_P + h_1 = v_F\,(P_2 - P_1) + h_1$$
$$S_1 = S_2 \qquad = 0.001043\,(1800 - 101.325) + 419.06 = 420.83 \text{ kJ/kg}$$

State 3

$$P_3 = 1800 \text{ kPa} \rightarrow h_3 = 2847.2 \text{ kJ/kg}$$
$$T_3 = 225\,^\circ\text{C}, \qquad S_3 = 6.4825 \text{ kJ/kg K}$$

State 4

$$P_4 = 325 \text{ kPa} \rightarrow X = S_4 - S_F/S_{FG} = 6.4825 - 1.7005/5.2645 = 0.908$$
$$S_4 = S_3 \qquad h_4 = h_F + X\,h_{FG} = 573.19 + (0.908)\,2155.4 = 2531.04 \text{ kJ/kg}$$

For, $\dot{m} = 23{,}000 \text{ kg/h} = 6.4 \text{ kg/s}$

$$\dot{Q}_{in} = \dot{m}\,(h_3 - h_2) = 6.4\,(2847.2 - 420.83) = 15501.8 \text{ kJ/s}$$
$$\dot{W}_t = \dot{m}\,(h_3 - h_4) = 6.4\,(2847.2 - 2531.04) = 2023.42 \text{ kJ/s} = 2.02 \text{ MW}$$

Appendix B: Theoretical Air Calculation for Combustion Process

Theoretical air for fiber

$$\text{Theoritical air}\left(\frac{\text{kg air}}{\text{kg fuel}}\right)=\frac{[(2.67\times 0.472)+(8\times 0.06)+(0.003)+(2.29\times 0.014)-(0.367)]}{0.23}=6.12\,\frac{\text{kg air}}{\text{kg fuel}}$$

$$\text{Including excess air}=6.12\times 1.2=7.344\,\frac{\text{kg air}}{\text{kg fuel}}$$

Theoretical air for shell

$$\text{Theoritical air}\left(\frac{\text{kg air}}{\text{kg fuel}}\right)=\frac{[(2.67\times 0.524)+(8\times 0.063)+(0.002)+(2.29\times 0.006)-(0.373)]}{0.23}=6.72\,\frac{\text{kg air}}{\text{kg fuel}}$$

$$\text{Including excess air}=6.72\times 1.2=8.064\,\frac{\text{kg air}}{\text{kg fuel}}$$

Theoretical air for EFB

$$\text{Theoritical air}\left(\frac{\text{kg air}}{\text{kg fuel}}\right)=\frac{[(2.67\times 0.435)+(8\times 0.057)+(0.0066)+(2.29\times 0.012)-(0.489)]}{0.23}=5.05\,\frac{\text{kg air}}{\text{kg fuel}}$$

$$\text{Including excess air}=5.05\times 1.2=6.06\,\frac{\text{kg air}}{\text{kg fuel}}$$

Appendix C: Biomass Composition and Required Air Calculation

For Qin = 15.5 MJ/s,
Biomass composition
(1) Fiber (70%):shell (30%):EFB (0%)
$m_F = 0.81$ kg/s × 70% = 0.567 kg/s
$m_S = 0.77$ kg/s × 30% = 0.231 kg/s
$m_{\text{EFB}} = 0.82$ kg/s × 10% = 0 kg/s

(2) Fiber (60%):shell (40%):EFB (0%)
$m_F = 0.81$ kg/s × 60% = 0.486 kg/s
$m_S = 0.77$ kg/s × 40% = 0.308 kg/s
$m_{\text{EFB}} = 0.82$ kg/s × 0% = 0 kg/s

(3) Fiber (70%):shell (20%):EFB (10%)
$m_F = 0.81$ kg/s × 70% = 0.567 kg/s
$m_S = 0.77$ kg/s × 20% = 0.154 kg/s
$m_{\text{EFB}} = 0.82$ kg/s × 10% = 0.082 kg/s

(4) Fiber (60%):shell (20%):EFB (20%)
$m_F = 0.81$ kg/s × 60% = 0.486 kg/s
$m_S = 0.77$ kg/s × 20% = 0.154 kg/s
$m_{\text{EFB}} = 0.82$ kg/s × 20% = 0.164 kg/s

(5) Fiber (50%):shell (30%):EFB (20%)
$m_F = 0.81$ kg/s × 50% = 0.405 kg/s
$m_S = 0.77$ kg/s × 30% = 0.231 kg/s
$m_{\text{EFB}} = 0.82$ kg/s × 20% = 0.164 kg/s

(6) Fiber (50%):shell (20%):EFB (30%)
$m_F = 0.81$ kg/s × 50% = 0.405 kg/s
$m_S = 0.77$ kg/s × 20% = 0.154 kg/s
$m_{\text{EFB}} = 0.82$ kg/s × 30% = 0.246 kg/s

(7) Fiber (70%):shell (10%):EFB (20%)
$m_F = 0.81$ kg/s × 70% = 0.567 kg/s
$m_S = 0.77$ kg/s × 10% = 0.077 kg/s
$m_{\text{EFB}} = 0.82$ kg/s × 20% = 0.164 kg/s

(8) Fiber (70%):shell (0%):EFB (30%)
$m_F = 0.81$ kg/s × 70% = 0.567 kg/s
$m_S = 0.77$ kg/s × 0% = 0 kg/s
$m_{\text{EFB}} = 0.82$ kg/s × 30% = 0.246 kg/s

Required air (excess air 20%)
(1) Comp. 1 → Fiber = 7.344 × 0.567 = 4.16 kg air/s
Shell = 8.064 × 0.231 = 1.86 kg air/s
EFB = 5.05 × 0 = 0 kg air/s
(2) Comp. 2 → Fiber = 7.344 × 0.486 = 3.57 kg air/s
Shell = 8.064 × 0.308 = 2.48 kg air/s
EFB = 5.05 × 0 = 0 kg air/s
(3) Comp. 3 → Fiber = 7.344 × 0.567 = 4.16 kg air/s
Shell = 8.064 × 0.154 = 1.24 kg air/s
EFB = 5.05 × 0.082 = 0.41 kg air/s
(4) Comp. 4 → Fiber = 7.344 × 0.486 = 3.57 kg air/s
Shell = 8.064 × 0.154 = 1.24 kg air/s
EFB = 5.05 × 0.164 = 0.83 kg air/s
(5) Comp. 5 → Fiber = 7.344 × 0.405 = 2.97 kg air/s
Shell = 8.064 × 0.231 = 1.86 kg air/s
EFB = 5.05 × 0.164 = 0.83 kg air/s
(6) Comp. 6 → Fiber = 7.344 × 0.405 = 2.97 kg air/s
Shell = 8.064 × 0.154 = 1.24 kg air/s
EFB = 5.05 × 0.246 = 1.24 kg air/s
(7) Comp. 7 → Fiber = 7.344 × 0.567 = 4.16 kg air/s
Shell = 8.064 × 0.077 = 0.62 kg air/s
EFB = 5.05 × 0.164 = 0.83 kg air/s
(8) Comp. 8 → Fiber = 7.344 × 0.567 = 4.16 kg air/s
Shell = 8.064 × 0 = 0 kg air/s
EFB = 5.05 × 0.246 = 1.24 kg air/s

Appendix D: Complete Calculation of the Emission Gases

						Component percentage					Component mass					Required O_2 to burn			
Fuel	Fraction	Fraction (%)	Mass	Fuel mass flow (kg/s)	Fuel mass flow total (kg/s)	C%	H_2%	S%	N_2%	O_2%	C (kg/s)	H_2 (kg/s)	S (kg/s)	N_2 (kg/s)	O_2 (kg/s)	C (2.67 kg)	H_2 (8 kg)	S (1 kg)	N_2 (2.29 kg)
Fiber	Fraction 1	0.7	0.81	0.567	0.798	47.2	6	0.3	1.4	36.7	0.267624	0.03402	0.001701	0.007938	0.208089	0.71455608	0.27216	0.001701	0.01817802
Shell		0.3	0.77	0.231		52.4	6.3	0.2	0.6	37.3	0.121044	0.014553	0.000462	0.001386	0.086163	0.32318748	0.116424	0.000462	0.00317394
EFB		0	0.82	0		43.52	5.72	0.66	1.2	48.9	0	0	0	0	0	0	0	0	0
Fiber	Fraction 2	0.6	0.81	0.486	0.794	47.2	6	0.3	1.4	36.7	0.229392	0.02916	0.001458	0.006804	0.178362	0.61247664	0.23328	0.001458	0.01558116
Shell		0.4	0.77	0.308		52.4	6.3	0.2	0.6	37.3	0.161392	0.019404	0.000616	0.001848	0.114884	0.43091664	0.155232	0.000616	0.00423192
EFB		0	0.82	0		43.52	5.72	0.66	1.2	48.9	0	0	0	0	0	0	0	0	0
Fiber	Fraction 3	0.7	0.81	0.567	0.803	47.2	6	0.3	1.4	36.7	0.267624	0.03402	0.001701	0.007938	0.208089	0.71455608	0.27216	0.001701	0.01817802
Shell		0.2	0.77	0.154		52.4	6.3	0.2	0.6	37.3	0.080696	0.009702	0.000308	0.000924	0.057442	0.21545832	0.077616	0.000308	0.00211596
EFB		0.1	0.82	0.082		43.52	5.72	0.66	1.2	48.9	0.0356864	0.00469	0.0005412	0.000984	0.040098	0.095282688	0.037523	0.000541	0.00225336
Fiber	Fraction 4	0.6	0.81	0.486	0.804	47.2	6	0.3	1.4	36.7	0.229392	0.02916	0.001458	0.006804	0.178362	0.61247664	0.23328	0.001458	0.01558116
Shell		0.2	0.77	0.154		52.4	6.3	0.2	0.6	37.3	0.080696	0.009702	0.000308	0.000924	0.057442	0.21545832	0.077616	0.000308	0.00211596
EFB		0.2	0.82	0.164		43.52	5.72	0.66	1.2	48.9	0.0713728	0.009381	0.0010824	0.001968	0.080196	0.190565376	0.075046	0.001082	0.00450672
Fiber	Fraction 5	0.5	0.81	0.405	0.8	47.2	6	0.3	1.4	36.7	0.19116	0.0243	0.001215	0.00567	0.148635	0.5103972	0.1944	0.001215	0.0129843
Shell		0.3	0.77	0.231		52.4	6.3	0.2	0.6	37.3	0.121044	0.014553	0.000462	0.001386	0.086163	0.32318748	0.116424	0.000462	0.00317394
EFB		0.2	0.82	0.164		43.52	5.72	0.66	1.2	48.9	0.0713728	0.009381	0.0010824	0.001968	0.080196	0.190565376	0.075046	0.001082	0.00450672
Fiber	Fraction 6	0.5	0.81	0.405	0.805	47.2	6	0.3	1.4	36.7	0.19116	0.0243	0.001215	0.00567	0.148635	0.5103972	0.1944	0.001215	0.0129843
Shell		0.2	0.77	0.154		52.4	6.3	0.2	0.6	37.3	0.080696	0.009702	0.000308	0.000924	0.057442	0.21545832	0.077616	0.000308	0.00211596
EFB		0.3	0.82	0.246		43.52	5.72	0.66	1.2	48.9	0.1070592	0.014071	0.0016236	0.002952	0.120294	0.285848064	0.11257	0.001624	0.00676008
Fiber	Fraction 7	0.7	0.81	0.567	0.808	47.2	6	0.3	1.4	36.7	0.267624	0.03402	0.001701	0.007938	0.208089	0.71455608	0.27216	0.001701	0.01817802
Shell		0.1	0.77	0.077		52.4	6.3	0.2	0.6	37.3	0.040348	0.004851	0.000154	0.000462	0.028721	0.10772916	0.038808	0.000154	0.00105798
EFB		0.2	0.82	0.164		43.52	5.72	0.66	1.2	48.9	0.0713728	0.009381	0.0010824	0.001968	0.080196	0.190565376	0.075046	0.001082	0.00450672
Fiber	Fraction 8	0.7	0.81	0.567	0.813	47.2	6	0.3	1.4	36.7	0.267624	0.03402	0.001701	0.007938	0.208089	0.71455608	0.27216	0.001701	0.01817802
Shell		0	0.77	0		52.4	6.3	0.2	0.6	37.3	0	0	0	0	0	0	0	0	0
EFB		0.3	0.82	0.246		43.52	5.72	0.66	1.2	48.9	0.1070592	0.014071	0.0016236	0.002952	0.120294	0.285848064	0.11257	0.001624	0.00676008

O_2 to be supplied (kg/s)	Required air (kg/kg fuel)	Required air + 20% excess air (kg air/kg fuel)	Produced GHG			Total GHG per fraction			Total GHG in 1 year (8760 h)			Total emission
			CO_2 (kg/s)	SO_2 (kg/s)	NO_2 (kg/s)	CO_2 (kg/s)	SO_2 (kg/s)	NO_2 (kg/s)	CO_2 (kg/year)	SO_2 (kg/year)	NO_2 (kg/year)	
0.7985061	3.471765652	4.166118783	0.9821801	0.003402	0.02611602	1.42641156	0.004326	0.03067596	44983314.96	136424.736	967397.0746	46087136.77
0.35708442	1.552540957	1.863049148	0.4442315	0.000924	0.00455994							
0	0	0	0	0	0							
0.6844338	2.97579913	3.570958957	0.8418686	0.002916	0.02238516	1.43417728	0.004148	0.02846508	45228214.7	130811.328	897674.7629	46256700.79
0.47611256	2.070054609	2.48406553	0.5923086	0.001232	0.00607992							
0	0	0	0	0	0							
0.7985061	3.471765652	4.166118783	0.9821801	0.003402	0.02611602	1.409303488	0.0051004	0.03239334	44443794.8	160846.2144	1021556.37	45626197.38
0.23805628	1.035027304	1.242032765	0.2961543	0.000616	0.00303996							
0.095502448	0.415228035	0.498273642	0.1309691	0.0010824	0.00323736							
0.6844338	2.97579913	3.570958957	0.8418686	0.002916	0.02238516	1.399961136	0.0056968	0.03189984	44149174.38	179654.2848	1005993.354	45334822.02
0.23805628	1.035027304	1.242032765	0.2961543	0.000616	0.00303996							
0.191004896	0.83045607	0.996547283	0.2619382	0.0021648	0.00647472							
0.5703615	2.479832609	2.97579913	0.7015572	0.00243	0.0186543	1.407726856	0.0055188	0.02968896	44394074.13	174040.8768	936271.0426	45504386.05
0.35708442	1.552540957	1.863049148	0.4442315	0.000924	0.00455994							
0.191004896	0.83045607	0.996547283	0.2619382	0.0021648	0.00647472							
0.5703615	2.479832609	2.97579913	0.7015572	0.00243	0.0186543	1.390618784	0.0062932	0.03140634	43854553.97	198462.3552	990430.3382	45043446.67
0.23805628	1.035027304	1.242032765	0.2961543	0.000616	0.00303996							
0.286507344	1.245684104	1.494820925	0.3929073	0.0032472	0.00971208							
0.7985061	3.471765652	4.166118783	0.9821801	0.003402	0.02611602	1.392195416	0.0058748	0.03411072	43904274.64	185267.6928	1075715.666	45165258
0.11902814	0.517513652	0.621016383	0.1480772	0.000308	0.00151998							
0.191004896	0.83045607	0.996547283	0.2619382	0.0021648	0.00647472							
0.7985061	3.471765652	4.166118783	0.9821801	0.003402	0.02611602	1.375087344	0.0066492	0.0358281	43364754.48	209689.1712	1129874.962	44704318.61
0	0	0	0	0	0							
0.286507344	1.245684104	1.494820925	0.3929073	0.0032472	0.00971208							

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