

Analysis of the Effect of Biomass Fuel Feed Rate on the Performance of a 30 Ton h⁻¹ Water-Tube Boiler in a Palm Oil Mill

Muhammad Fajar ^{1✉}, Zulham Effendi ²

(1,2) Study Program of Plantation Product Processing Technology, Institut Teknologi Sawit Indonesia, Medan, Indonesia

Abstract: Boilers are among the most important utility units in palm oil mills because they supply steam required for processing fresh fruit bunches. Boiler operating performance is strongly influenced by the biomass fuel feed rate, which directly affects heat generation, steam production, and thermal efficiency. This study aimed to determine the optimum biomass fuel feed rate for boiler operation and to evaluate its relationship with steam production in a 30 ton h⁻¹ water-tube boiler. A quantitative descriptive approach was employed using operational log sheet data, field observations, and laboratory analyses of biomass fuel characteristics. The observed parameters included fiber and palm kernel shell feed rates, fuel heating value, steam flow rate, steam pressure, steam temperature, feedwater temperature, and boiler thermal efficiency. Boiler efficiency was calculated using the direct method based on the energy balance between heat input and heat output. The results showed that increasing the biomass fuel feed rate increased both total heat input and steam production. Boiler thermal efficiency increased from 61.15% during the initial operating period to a maximum of 71.22% under optimum operating conditions. However, further increases in fuel feed rate did not improve boiler performance, as the efficiency decreased to 70.64%, indicating reduced combustion effectiveness and heat transfer efficiency. These findings demonstrate that proper regulation of biomass fuel feed rate is essential for maintaining stable steam production and achieving optimum thermal efficiency in palm oil mill boiler operations.

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INTRODUCTION

Indonesia is one of the world's largest producers of crude palm oil (CPO), and the palm oil industry plays a significant role in supporting the national economy. The sustainability of palm oil processing depends not only on production efficiency but also on the reliability of utility systems that provide thermal and electrical energy. Among these utility systems, boilers are the primary equipment responsible for generating steam required for sterilization, digestion, pressing, clarification, and power generation. Therefore, maintaining optimum boiler performance is essential to ensure continuous processing and improve the overall operational efficiency of palm oil mills (Naibaho, 2016; Rahardja et al., 2021; Basiron, 2007). Efficient boiler operation also supports sustainable energy utilization by maximizing the use of renewable biomass resources while reducing dependence on fossil fuels (Bazmi et al., 2011).

Unlike conventional industrial boilers that rely on fossil fuels, boilers in palm oil mills utilize biomass residues generated during processing, namely palm pressed fiber and palm kernel shell, as their primary fuel. These biomass materials are renewable energy sources with relatively high heating values and are capable of supplying the steam demand required during palm oil processing. However,

the combustion performance of biomass fuels is strongly influenced by several factors, including fuel feed rate, moisture content, particle size, fuel composition, and heating value. Variations in these characteristics directly affect combustion stability, heat release, steam generation, and boiler thermal efficiency (Kunarto, 2018; Husain et al., 2003; Saidur et al., 2011; Bhuiyan et al., 2018).

Among these factors, biomass fuel feed rate is one of the most critical operational parameters because it determines the amount of thermal energy supplied to the combustion chamber. Insufficient fuel feeding reduces heat generation, resulting in unstable steam production and decreased boiler performance. Conversely, excessive fuel feeding may lead to incomplete combustion, increase heat losses, and reduce thermal efficiency because not all of the supplied fuel can be converted into useful heat. Therefore, proper regulation of biomass fuel feed rate is essential to maintain efficient boiler operation and stable steam production under varying operating conditions (Çengel & Boles, 2015; Bazmi et al., 2011; Saidur et al., 2011). Previous studies have also demonstrated that optimizing biomass combustion improves heat transfer efficiency and minimizes thermal losses, thereby enhancing the overall performance of industrial boilers (Bhuiyan et al., 2018).

Previous studies have demonstrated that boiler performance is closely associated with biomass fuel characteristics, combustion efficiency, and cogeneration systems in palm oil mills. Husain et al. (2003) reported that the quality of palm pressed fiber and palm kernel shell significantly influences boiler thermal efficiency and overall energy utilization. Bazmi et al. (2011) emphasized that optimizing the utilization of oil palm biomass is essential for improving energy efficiency and reducing dependence on fossil fuels. In addition, efficient biomass-fired boiler operation contributes to stable steam production and electricity generation through cogeneration systems widely implemented in palm oil mills (Effendi et al., 2021; Ansori et al., 2014). Nevertheless, studies specifically evaluating the influence of biomass fuel feed rate on the operational performance of industrial-scale 30 ton h⁻¹ water-tube boilers using actual operating data remain limited. Since boiler operating conditions vary according to production load, biomass characteristics, and mill operating practices, further investigation is required to determine the optimum biomass fuel feed rate capable of maintaining stable steam production while maximizing boiler thermal efficiency.

Therefore, this study was conducted to analyze the effect of biomass fuel feed rate on the performance of a 30 ton h⁻¹ water-tube boiler in a palm oil mill. The analysis was performed using operational data, field observations, laboratory analysis of biomass fuel characteristics, and energy balance calculations based on the direct method. The evaluated parameters included biomass fuel feed rate, fuel heating value, steam production, heat input, heat output, and boiler thermal efficiency. The findings of this study are expected to provide practical information regarding the optimum utilization of biomass fuel to improve boiler performance and support more efficient energy management in palm oil mill operations.

The results of this study are expected to serve as a basis for system improvements to ensure the boiler operates more efficiently and energy-efficiently, thereby supporting the operational sustainability of the 30-ton/hour palm oil mill.

RESEARCH METHOD

Research Design

This study employed a quantitative descriptive research design to analyze the effect of biomass fuel feed rate on boiler performance in a 30 ton h⁻¹ water-tube boiler at the Palm Oil Mill of PTPN IV Regional I. The research was conducted under actual operating conditions using operational data obtained from the mill. Data collection involved direct field observations, operational log sheets, laboratory analysis of biomass fuel characteristics, and technical documentation related to boiler operation. The study focused on evaluating the relationship between biomass fuel feed rate, heat input, steam production, and boiler thermal efficiency.

Data Collection

Primary and secondary data were used in this study. Primary data were obtained through direct observation of boiler operating conditions, while secondary data were collected from operational log sheets, laboratory reports, equipment specifications, and other supporting technical documents over a 6-day period, and five times daily every 2 hours starting from the start of the Palm Oil Mill processing.

The observed parameters included biomass fuel feed rate (fiber and palm kernel shell), fuel heating value, steam production rate, steam pressure, steam temperature, feedwater temperature, and boiler operating capacity. These parameters were used to evaluate the thermal performance of the boiler under different operating conditions.

Data Analysis

Boiler performance was evaluated using the direct method, in which boiler thermal efficiency was determined from the ratio of useful heat output to total heat input. The heat input was calculated from the biomass fuel feed rate and its heating value, whereas the useful heat output was determined from the steam production rate and the enthalpy difference between steam and feedwater.

$$n = \frac{m_s \times (h_s - h_w)}{Q_{total} \times 4,184} \times 100$$

n = Boiler thermal efficiency (%)

m_s = Steam flow rate (kg h⁻¹)

h_s = Specific enthalpy of steam (kJ kg⁻¹)

h_w = Specific enthalpy of feedwater (kJ kg⁻¹)

Q_{total} = Total heat energy supplied by biomass fuel (kcal h⁻¹)

4,184 = Conversion factor from kcal to kJ.

The calculated data were analyzed descriptively to evaluate the relationship between biomass fuel feed rate and boiler performance. The results were interpreted to determine the optimum biomass fuel feed rate capable of producing stable steam generation and improving boiler thermal efficiency.

RESULTS AND DISCUSSION

Biomass Fuel Feed Rate

Biomass fuel used in the boiler consisted of palm pressed fiber and palm kernel shell generated during the palm oil milling process. Fiber served as the primary fuel, while shell functioned as a supplementary fuel to improve combustion stability and increase the overall heating value. The utilization of these biomass residues supports renewable energy implementation in palm oil mills by maximizing the use of processing by-products while reducing dependence on fossil fuels. Previous studies have shown that proper biomass fuel management contributes to improved boiler performance, higher thermal efficiency, and lower particulate emissions in palm oil mill operations (Nasrin et al., 2019; Naibaho, 2016).

During the observation period, biomass fuel consumption was recorded every two hours from 08:00 to 16:00. Fiber consumption ranged from 4.39 to 4.80 ton h⁻¹, whereas shell consumption ranged from 1.18 to 1.44 ton h⁻¹. Fuel consumption was lowest at 08:00 during the initial operating period and gradually increased as steam demand increased. The highest biomass consumption occurred at 12:00, when fiber and shell feed rates reached 4.80 ton h⁻¹ and 1.44 ton h⁻¹, respectively. Throughout the observation period, fiber contributed approximately 78% of the total biomass fuel, while shell accounted for approximately 22%, indicating a relatively constant fuel mixture during boiler operation.

Table 1. Average Biomass Fuel Feed Rate at Different Operating Hours

Operating Time	Fiber (ton h ⁻¹)	Palm Kernel Shell (ton h ⁻¹)
08:00	4.39	1.18
10:00	4.59	1.26
12:00	4.80	1.44
14:00	4.67	1.33
16:00	4.77	1.42

The gradual increase in biomass fuel feed rate reflects the increasing steam demand during mill operation. As more biomass is supplied to the furnace, a greater amount of chemical energy becomes available for combustion, resulting in higher heat release for steam generation. Therefore, maintaining an appropriate fuel feed rate is essential to ensure stable combustion, minimize heat losses, and achieve efficient boiler operation (Çengel & Boles, 2015; Bhuiyan et al., 2018).

The predominance of palm pressed fiber observed in this study is consistent with common operating practices in palm oil mills because fiber is produced in larger quantities than palm kernel shell during fresh fruit bunch processing. Although shell is available in smaller quantities, it possesses a higher calorific value and is commonly blended with fiber to improve combustion stability, maintain furnace temperature, and enhance boiler performance. Maintaining a relatively constant fiber-to-shell ratio, as observed throughout the operating period, provides a more stable heat supply and contributes to consistent steam production (Nasrin et al., 2019).

The results of this study indicate that the increase in biomass fuel feed rate followed the increase in steam demand without causing significant fluctuations in the fuel composition. This finding suggests that maintaining a stable biomass fuel mixture is an important operational strategy for achieving consistent boiler performance. Similar studies have reported that appropriate biomass fuel composition and stable combustion conditions improve thermal efficiency while reducing combustion losses and particulate emissions (Nasrin et al., 2019; Bhuiyan et al., 2018).

Heating Value of Biomass Fuel

The heating value of biomass fuel was evaluated based on moisture content, residual oil, and non-oil solids (NOS), as these parameters determine the amount of thermal energy released during combustion. Moisture content is considered one of the most influential factors affecting biomass combustion because part of the released heat is consumed to evaporate water before the fuel reaches complete combustion. In contrast, higher oil and fixed combustible components generally increase the calorific value of biomass fuel by providing additional combustible matter during the oxidation process (Kuswa et al., 2024; Nasrin et al., 2019).

Palm kernel shell exhibited heating values ranging from 3827.04 to 3910.54 kcal kg⁻¹. The highest value occurred when moisture content decreased to 15.70%, whereas the lowest value was observed when moisture content increased to 17.26%. These results indicate that higher moisture content reduced the effective heating value because part of the combustion energy was consumed to evaporate water before combustion proceeded efficiently.

Table 2. Heating value of palm kernel shell

Shell (ton h ⁻¹)	Oil (%)	Moisture (%)	NOS (%)	Heating Value (kcal kg ⁻¹)
1.18	1.06	16.09	82.85	3890.69
1.26	1.02	16.03	82.95	3892.23
1.44	1.02	17.26	81.72	3827.04
1.33	1.01	16.27	82.72	3879.10
1.42	1.04	15.70	83.26	3910.54

Fiber showed lower heating values than shell, ranging from 2309.95 to 2414.58 kcal kg⁻¹, mainly because of its higher moisture content. However, fiber remained the major contributor to boiler heat generation because its consumption rate was substantially higher. The highest heating value was achieved when moisture content decreased to 37.24%, while residual oil and NOS reached their highest values.

Table 3. Heating value of palm pressed fiber

Fiber (ton h ⁻¹)	Oil (%)	Moisture (%)	NOS (%)	Heating Value (kcal kg ⁻¹)
4.39	4.38	39.48	56.14	2309.95
4.59	4.21	38.56	57.23	2342.47
4.80	4.32	38.09	57.59	2368.83
4.74	4.29	38.27	57.44	2359.34
4.77	4.48	37.24	58.28	2414.58

BOILER PERFORMANCE

Effect of Biomass Fuel Feed Rate on Steam Production

Increasing biomass fuel feed rate was followed by a corresponding increase in steam production throughout the observation period. Total thermal energy supplied to the boiler increased from 14.73 million kcal h⁻¹ at 08:00 to 17.09 million kcal h⁻¹ at 16:00, while steam production increased from 19.36 ton h⁻¹ to 26.87 ton h⁻¹.

Between 12:00 and 14:00, steam production continued to increase despite a slight decrease in heat input. This condition indicates that combustion and heat transfer were more effective during this operating period, allowing the boiler to generate additional steam without requiring greater energy input.

Table 4. Relationship between biomass fuel feed rate and steam production

Time	Shell (ton h ⁻¹)	Fiber (ton h ⁻¹)	Total Energy (kcal h ⁻¹)	Steam Flow (ton h ⁻¹)	Steam Temperature (°C)	Steam Enthalpy (kJ kg ⁻¹)
08:00	1.18	4.39	14,731,694.70	19.36	208.31	2353.50
10:00	1.26	4.59	15,687,284.94	22.04	211.61	2322.90
12:00	1.44	4.80	16,888,975.68	25.21	212.90	2309.00
14:00	1.33	4.74	16,367,428.36	25.86	212.39	2314.70
16:00	1.42	4.77	17,086,155.56	26.87	212.33	2315.40

Boiler Thermal Efficiency

Boiler thermal efficiency increased steadily from 61.15% at 08:00 to a maximum of 71.22% at 14:00. At this operating condition, the boiler produced 25.86 ton h⁻¹ of steam with a heat input of 68.48 million kJ h⁻¹, indicating efficient combustion and effective heat transfer.

Although both heat input and steam production reached their highest values at 16:00, thermal efficiency decreased slightly to 70.64%. This finding indicates that increasing biomass fuel feed rate

beyond the optimum operating condition did not proportionally improve useful heat output. Instead, part of the additional combustion energy was likely lost through flue gases and other heat losses.

The increase in boiler efficiency from 61.15% at the start of the shift (8:00 AM) to a peak of 71.22% at 2:00 PM occurred because the initial combustion energy, which was initially largely absorbed for heating the furnace, shifted to optimum working conditions, where the fuel and air ratio was at its most balanced point so that heat absorption by the feed water was maximized. However, efficiency decreased to 70.64% at 4:00 PM due to the phenomenon of overfeeding or excessive biomass feeding to achieve maximum steam production; the combustion rate that exceeded the absorption capacity of the boiler pipe caused most of the thermal energy not to be converted into steam, but was wasted as flue gas loss through the chimney and triggered incomplete combustion, in line with the literature of (Mulyani et al. 2023; He et al. 2023; Simanjuntak 2023; Ramadhan et al. 2024; and the Center for Energy Technology 2015)

Overall, the results demonstrate that biomass fuel feed rate significantly affected boiler performance. Higher fuel feed rates increased steam production; however, the highest thermal efficiency was achieved at an optimum operating condition rather than at the maximum fuel consumption level.

Table 5. Boiler thermal efficiency

Time	Total Energy (kcal h ⁻¹)	Heat Input (kJ h ⁻¹)	Steam Production (ton h ⁻¹)	Heat Output (kJ h ⁻¹)	Efficiency (%)
08:00	14,731,694.70	61,637,411	19.36	37,692,952	61.15
10:00	15,687,284.94	65,635,600	22.04	41,590,608	63.36
12:00	16,888,975.68	70,663,474	25.21	47,444,272	67.14
14:00	16,367,428.36	68,481,320	25.86	48,777,907	71.22
16:00	17,086,155.56	71,488,475	26.87	50,501,087	70.64

CONCLUSION

This study demonstrated that biomass fuel feed rate significantly affected the performance of the water-tube boiler operated at the palm oil mill. The average biomass fuel consisted of 4.39-4.80 ton h⁻¹ of palm pressed fiber and 1.18-1.44 ton h⁻¹ of palm kernel shell, with fiber contributing approximately 78% of the total fuel mixture. Variations in moisture content influenced the heating value of both biomass fuels, where lower moisture content produced higher heating values and improved combustion quality.

An increase in biomass fuel feed rate increased the total heat input and steam production. Steam generation increased from 19.36 ton h⁻¹ during the initial operating period to 26.87 ton h⁻¹ at the highest fuel feed rate. However, the highest steam production did not correspond to the highest thermal efficiency.

Boiler thermal efficiency increased from 61.15% at the beginning of operation to a maximum value of 71.22%, after which efficiency slightly decreased to 70.64% despite a further increase in fuel feed rate. This finding indicates that excessive biomass fuel feeding does not necessarily improve boiler performance because additional combustion energy cannot be fully converted into useful heat for steam generation. Therefore, maintaining an optimum biomass fuel feed rate is essential for achieving stable steam production and maximizing boiler thermal efficiency in palm oil mill operations.

The results of this study provide empirical evidence regarding the thermal efficiency threshold of a 30-ton-hour industrial-scale water tube boiler.¹ These data can be used as a reference or input parameter for thermodynamic simulation modeling and boiler efficiency curves in the palm oil industry.

This research opens up space for further research, such as testing an automatic fuel feeder system based on real-time water content and combustion chamber temperature sensors, in order to consistently maintain optimum operating conditions.

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