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Energy, Exergy and Environmentally Sustainable Process Analysis of Biomass Boilers Using Different Palm Oil Waste

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ABSTRACT: This investigation examines the combustion of 13 distinct forms of Malaysian palm oil waste in boilers, focusing on energy efficiency and exergy efficiency analysis. Energy efficiency measures how well the combustion process converts the chemical energy of the biomass into usable heat energy. The study reveals an energy efficiency range from 68.58%–81.96%, with an average of 76.68%, indicating the variability in biomass performance. Exergy efficiency averages at 22.45%, with a range from 20.42%–23.75%, underscoring the need for further optimisation in energy transformation. A parameter study of different air fuel ratios (AFR) was also conducted. Additionally, boiler's energy and exergy efficiency were compared to those reported in other studies, and the findings were consistent. The simulation results showed that the primary sources of energy loss due to irreversibility of the process in the boiler system are the combustion chamber, followed by the heat exchanger. Enhancing combustion processes and exploring advanced technologies could improve the sustainability of biomass energy systems, offering a pathway to reduce reliance on nonrenewable fuels and mitigate environmental impact.

Keywords: energy, exergy, aspen plus, biomass combustion, boiler

1. INTRODUCTION

There is an increasing need for alternative and sustainable energy sources because of concerns about climate change, environmental sustainability and energy availability. Conventional fossil fuels, including coal, oil and natural gas, have traditionally dominated the universal energy generation.[1] Nevertheless, the alarming risk of fuel deficiency requires instantaneous action to detect renewable energy replacements. Agricultural biomass leftovers, such as wastes from palm oil, rice husk and wheat straw, additionally municipal solid waste (MSW), are promising resources of renewable energy. Currently, approximately 13% of the world's energy requirements are met by biomass waste transformation.[2] In 2022, Malaysia produces approximately

7.4 milliontonnes of palm waste, including empty fruit bunches (EFB), palm kernel shells (PKS) and palm oil mill effluent.[2] If these secondary products are not handled accurately, they can trigger environmental-economic equilibrium problems of pollution. Like other biomass sources, Malaysian palm oil wastes helped reduce greenhouse gas emissions and dependency on non-renewable resources by providing a renewable substitute for conventional fossil fuels. There are various techniques for converting biomass waste into energy, including thermo chemical and biochemical processes. Biomass combustion is widely used to transform palm waste into renewable energy in the processing industry.[3]

Understanding the combustion characteristics of biomass, such as empty fruit bunch, PKS and palm oil mill effluent, is crucial for maximising energy production. Analysing and optimising these characteristics plays a pivotal role in enhancing the performance of biomass combustion. Simulation studies using advanced engineering software like Aspen Plus®, Ansys Fluent provide valuable insights into optimising power generation from oil palm biomass.[4] The study aims to understand the behaviour and performance of palm oil biomass-based fuels in the power generation process. Numerous studies have shown promising results in biomass combustion studies, including efficiency, emissions and ash behaviour analysis.[5,6] Modelling biomass combustion is well-established, with Gibbs free energy minimisation being a key technique in Aspen Plus®.[6,7]

The primary objective of this study is to simulate a biomass combustion boiler process using Aspen Plus®, as well as conduct thermodynamic assessments to measure performance and examine various biomass feedstocks for combustion suitability. Emphasising both energetic and exergetic performance, the study provides a comprehensive understanding of combustion characteristics. Thirteen distinct samples of palm oil biomass waste from Malaysia, specifically including oil palm frond (OPF), PKS, EFB and palm mesocarp fiber (PMF), are analysed to reveal the varying combustion behaviours of these biomass types, ultimately contributing to optimised energy production strategies. This analysis reveals the varying combustion behaviours of these biomass types, ultimately contributing to optimised energy production strategies. By conducting energy and exergy analyses on these various samples, the study provides valuable insights into their combustion behaviour and characteristics, including detailed procedural steps. While previous studies have demonstrated varying degrees of success in biomass combustion exergy analysis, there remains a scarcity of research specifically focused on the performance of Malaysian palm oil waste in this context.[8–10]

Additionally, this evaluation explores how palm waste combustion can enhance environmental sustainability. The research examines the energy yield and exergy efficiency from these samples, highlighting responsible resource management practices. This approach contributes significantly to Malaysia's development of a circular economy by converting waste into energy and by taking measures to minimise environmental impact. A circular economy system decreases waste while increasing resource efficiency, ensuring that items can be utilised and transformed rather than abandoned. This primarily reduces the amount of waste transferred to landfills, but it also reduces consumption on fossil fuels, decreasing greenhouse gas emissions and enhancing the energy sector's sustainability in general. The conversion of palm oil biomass waste into energy offers significant advantages for the environment, namely reduced pollution and the preservation of natural resources. Malaysia has the potential to provide a sustainable energy solution that solves both supply and demand and environmental concerns by converting all of this waste into renewable energy. This is consistent with worldwide efforts to transition to renewable energy sources and address climate change.

Furthermore, this study conducts a parametric analysis of air-fuel ratio (AFR) variations with different biomass feedstocks during boiler combustion. The air-to-fuel ratio significantly influences combustion efficiency and effectiveness. The study enhances the understanding of how AFR variations influence the combustion efficiency of different biomass feedstocks. By transforming biomass waste into energy and lowering reliance on fossil fuels, the study contributes to improving environmental sustainability.

2. MATERIALS AND METHODS

2.1 Biomass Source

In the present study, 13 distinct biomass samples widely reported in the literature were utilised, as feedstock for boiler combustion as shown in Figure 1.[11–19] These samples encompass a range of materials, including PKS, EFB, OPF and PMF, sourced from Malaysia. The carbon content of these samples varies from 43.53%–51.77%. Hydrogen content varies between 5.30% and 7.33%, while oxygen content ranges from 34.10%–47.09%. Sulfur and nitrogen peak at 0.92% and 2.18%, respectively, with sulfur having the highest and nitrogen the lowest concentrations. Volatile matter demonstrates variability ranging from 67.01%–83.38%. The fixed carbon content ranges from 8.60%–19.70%, and moisture content varies significantly from 1.74% and 15.77%. The ash content ranges from 0.4%–6.9%.

In addition, the higher heating values (HHV) of the samples range from 18.67 $MJkg^{-1}$–22.48 $MJkg^{-1}$, while the lower heating values (LHV) range between 17.48 $MJkg^{-1}$ and 20.89 $MJkg^{-1}$. PKS samples typically exhibit high fixed carbon and moderate moisture content, with HHVs ranging between 19.11 $MJkg^{-1}$ and 21.03 $MJkg^{-1}$ and LHVs ranging from 17.78 $MJkg^{-1}$ to 19.59 $MJkg^{-1}$. EFB exhibits significant variation in moisture and ash content, affecting its fuel efficiency, but shows high HHVs from 19.33 $MJkg^{-1}$–22.48 $MJkg^{-1}$ and LHVs from 17.70 $MJkg^{-1}$–20.89 $MJkg^{-1}$. PMF showcases an HHV of 19.07 $MJkg^{-1}$ and an LHV of 17.77 $MJkg^{-1}$, reflecting high volatile matter and low moisture content. On the other hand, OPF demonstrates the highest ash level, with HHV and LHV recorded at 18.67 $MJkg^{-1}$ and 17.48 $MJkg^{-1}$, respectively. These Malaysian biomass samples exhibit a diverse composition, which shows their potential as important renewable resources for the generation of sustainable energy. The range of chemical properties allows for the examination of various combustion behaviours, making them valuable for understanding the energy performance of different biomass types.

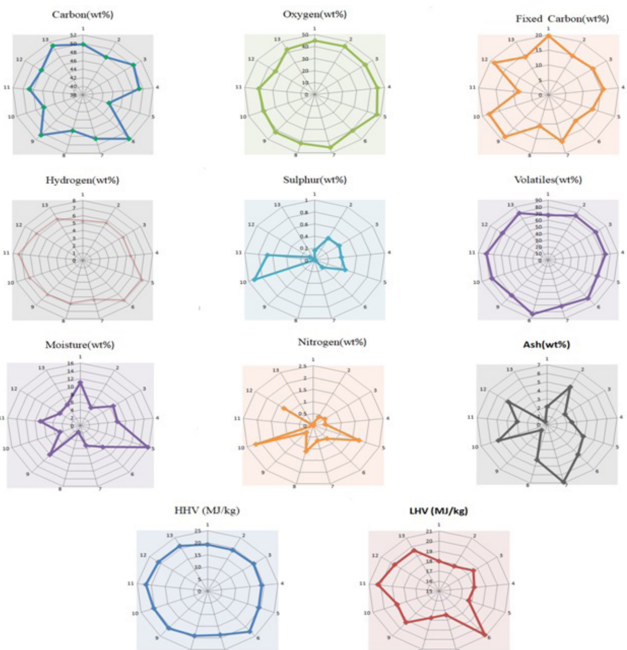

Figure 1: Ultimate analysis and proximate analysis, LHV and HHV of widely reported different types of biomass feedstock.[11–19]

2.2 Simulation in Aspen Plus®

Aspen Plus® (V11) was used to generate a process model for the biomass boiler as shown in Figure 2. Aspen Plus® is one of the important numerical tools in chemical process modelling, capable of managing both solids and fluids, making it particularly useful for the biomass combustion. The software's comprehensive property database enhances its utility. In this study, the Peng-Robinson-Boston-Mathias (PR-BM) thermodynamic method was employed to model the steady-state system.[5] A fuel flow rate of 1.65 $kghr^{-1}$ was specifically selected for the simulations to replicate the conditions of the experimental study conducted by Wiinikka et al.[10] These parameters were chosen to closely align with the laboratory-scale combustion chamber utilised in their research.

Therefore, the simulation takes into consideration the following assumptions:

- Flow rate of biomass feed was 1.65 kgh^{-1}.
- Stream of inlet was at 1 atm and 30°C.
- The input of biomass was transformed into standard Aspen Plus® components based on proximate and ultimate evaluation, and it was considered non-conventional.

A non-conventional solid, termed as solid with metric unit was used as the feedstock in this investigation. Non-conventional solids are characterised by Aspen Plus® utilising empirical variables known as component attributes. Utilising the stream class MIXCNIC, both solid and unconventional components are processed by MIX, while conventional components are processed by NIC. Enthalpy and density are determine utilising the HCOALGEN and DCOALIGT property sets, treating the biomass feedstock, analogous to coal. The modelling system incorporates the biomass's proximate and ultimate analytical values. To remove excess moisture, the biomass feedstock is initially dried at 150°C in a stoichiometric reactor within a drier block. In the breakdown stage, a yield-based reactor (RYIELD) converts the unconventional constituents of the dehydrated input into conventional constituents. A decomposition reactor processes the yield reactor's stream at 400°C and 1 atm. The stream then enters a combustion chamber where heat is released, andthe resulting hot flue gases enter a heat exchanger. The condenser's cooling temperature is kept at 100°C.[20]

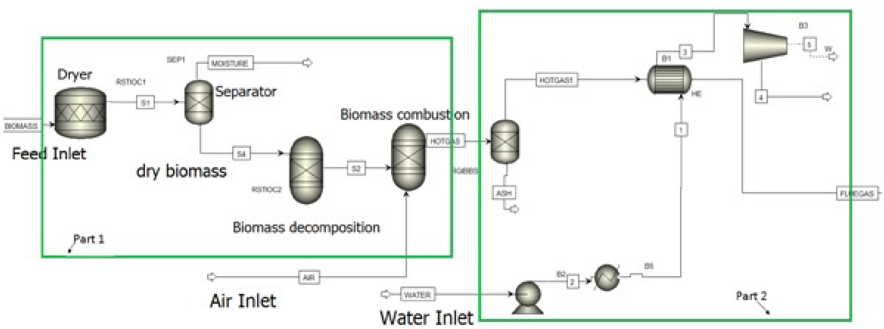

Figure 2: Aspen Plus® process flow diagram for biomass combustion boiler.

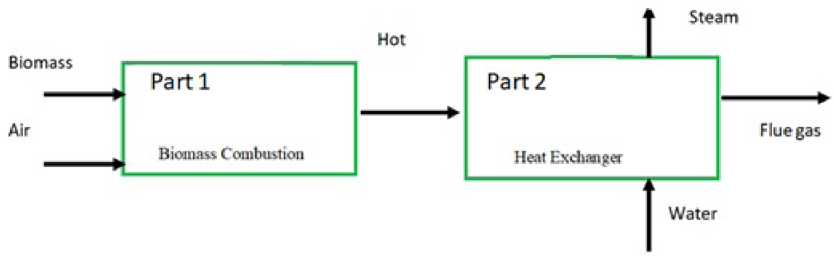

Figure 3: Reduce form boiler.

2.3 Parameter Analysis of AFRBiomass

The AFR values selected for this study 1, 4.5, 8.5 and 9.5 were based on the experimental setup, which utilised a fuel flow rate of 1.65 $kghr^{-1}$ and an air flow rate of 13.94 $kghr^{-1}$, resulting in an approximate AFR of 8.5. The lower AFR values (1 and 4.5) were chosen to examine the effects of inadequate and moderate excess air on combustion characteristics, allowing for the assessment of stability and efficiency at lower airflow conditions. In contrast, the higher value (9.5) aimed to evaluate the influence of increased air supply on combustion efficiency and emissions. This strategic selection of AFR values enables a thorough investigation into the combustion behaviour across a spectrum of operating conditions, thereby enhancing the understanding of the impact of AFR variations on the performance and environmental implications of biomass combustion.

2.4 Sustainability Assessment in Methodology

The sustainability focus of this study is evaluated through the assessment of energy and exergy efficiencies derived from the combustion of palm biomass waste. The methodology emphasises the conversion of palm waste into energy, thereby contributing to sustainability by minimising waste and utilising renewable resources. An energy balance analysis determines the significant energy content of the biomass and evaluates how combustion processes release energy for boiler operation. This approach ensures an emphasis on efficient energy conversion and effective waste management practices, reinforcing the study's commitment to renewable energy goals.

3. ENERGY AND EXERGY ANALYSIS

Boiler system converts the fuel into thermal energy for steam production, essential in power generation. Traditional energy analysis, based on the first law of thermodynamics, focuses on energy conservation, ensuring that energy input equals output. However, it does not account for energy quality or losses due to entropy. Exergy analysis, which integrates the first and second laws of thermodynamics, evaluates energy quality and identifies losses due to irreversibility. When applied to a boiler's heat exchanger and combustion chamber, exergy analysis calculates inefficiencies in both combustion and heat transfer processes. By highlighting these inefficiencies and suggesting system modifications to reduce irreversibility, exergy analysis effectively enhances power generation systems beyond the capabilities of standard energy analysis.

To simplify the understanding of the entire process in a boiler system, the system can be divided into two parts as shown in Figure 3: the combustion chamber (Part 1) and the heat exchanger (Part 2). In the combustion chamber, biomass (fuel) and air are the inputs, producing hot gas. Energy analysis in this part tracks the conversion of energy from biomass into thermal energy in the hot gases. Whereas the exergy analysis calculates the chemical exergy of the biomass and physical exergy of the air and categorises losses due to irreversibility during combustion. In the heat exchanger, the inputs are hot gas and cold water, resulting in the production of steam and flue gas. Energy analysis monitors the transfer of thermal energy from hot gas to cold water, producing steam. Exergy analysis assesses the thermal exergy of hot gas and the physical exergy of cold water, determining exergy destruction due to irreversibility in the heat transfer process.

Overall energy balance over boiler

$$E_{biomass} + E_{air} = E_{steam} + E_{flue\ gas} \tag{1}$$

where, $E_{biomass}$ and E_{air} represent the energy contents of input and E_{steam} and $E_{flue\ gas}$ represent the energy contents of output streams, respectively. Generally, kinetic energy and potential energy values are relatively small and, thus, negligible in the analysis.

Overall exergy balance over boiler

$$Ex_{biomass} + Ex_{air} = Ex_{steam} + Ex_{flue\ gas} + I \tag{2}$$

where, $Ex_{biomass}$ and Ex_{air} represent the exergy contents of input and Ex_{steam} and $Ex_{flue\ gas}$ represent the exergy contents of output streams, I represent destruction, respectively.

Combustion chamber

Energy balance equation for combustion chamber:

$$E_{biomass} + E_{air} = E_{hot\ gas} \tag{3}$$

where, $E_{biomass}$ and E_{air} represent the energy contents of input, $E_{flue\ gas}$ represents the output streams.

Exergy balance equation for combustion chamber:

$$Ex_{biomass} + Ex_{air} = Ex_{hot\ gas} \tag{4}$$

where, $Ex_{biomass}$ and Ex_{air} represent the exergy contents of input while $Ex_{flue\ gas}$ represent the output streams.

$$E_{air} = m_{air}\ x\ C_p \times (T_{air} - T_{ref}) \tag{5}$$

Here, m_{air} is the mass flow rate of the air, C_p is the specific heat capacity of the air at constant pressure, T_{air} is the temperature of the incoming air, and T_{ref} is the reference temperature.

Biomass energy:

$$E_{biomass} = m_{biomass} \times LHV_{biomass} \tag{6}$$

The LHV of biomass is estimated using the equations as follows:[21]

$$LHV_{biomass} = HHV_{biomass} - (9 \times \%\ \mathrm{H} \times h_{fg}) \tag{7}$$

The calculation of biomass chemical exergy, as per the equation by Szargut and Styrylska gives:[22]

Exergy of biomass:

$$Ex_{biomass} = \beta_{biomass} \times m_{biomass} \times LHV_{biomass} \tag{8}$$

Correlation factor for biomass:

$$\beta_{biomass} \frac{\left[\left(1.0414 + 0.0177 \times \left[\frac{H}{C}\right]\right) - 0.3328\left(\frac{O}{C}\right) \times \left(1 + 0.0537 \times \left[\frac{H}{C}\right]\right)\right]}{\left(1 - 0.421\frac{O}{C}\right)} \tag{9}$$

where, H, C and O stand for the mass fractions of hydrogen, carbon and oxygen in the biomass material, correspondingly.

Energy hot product gas:

$$E_{biomass} = m_{gas} \times C_p \times (T_{hot\ gas} - T_{ref}) \tag{10}$$

where, $E_{hot\ gas}$ represents the exergy content of the hot gas, m_{gas} is the mass flow rate of the hot gas, C_p is the specific heat capacity of the hot gas at constant pressure, $T_{hot\ gas}$ is the temperature of the hot gas, and T_{ref} is the reference temperature.

Exergy equation for hot gas:

$$Ex_{hot\ gas} = Ex_{ch} + Ex_{ph} \tag{11}$$

where, Ex_{ph} and Ex_{ch} represent the physical and chemical exergy contents of streams, respectively. Physical exergy deals with the processes having a constant chemical composition from given state to the restricted dead state. The physical exergy a gas flow is calculated as:

$$Ex_{ph} = \sum \frac{n}{1}[(h - h_0) - T_0(s - s_0)] \tag{12}$$

where, h and s denote the specific enthalpy and entropy at the state described by temperature T while h_0 and s_0 are the enthalpy and entropy, respectively under ambient conditions with a temperature of T_0 (298 K) and a pressure of 1 atm, as shown in Table 1. The change in chemical composition of the working substance is associated with the processes of combustion and therefore, the inclusion of chemical exergy has become the integral part of the exergy analysis for these two processes. Chemical exergy of a material stream is computed after applying Equation 13.

Chemical exergy of combustion products:

$$Ex_{ph} = \sum \frac{n}{1}[(x_i)(e_{ich} + RT_0 \text{ In } (x_i)] \tag{13}$$

x_i is the mole fraction of component i in the mixture, e_{ich} is the standard chemical exergy of the gases component, R is the universal gas constant. T_0 is the reference temperature (usually the ambient temperature).

Heat Exchanger

Energy balance equation for heat exchanger:

$$E_{hot\ gas} + E_{water} = E_{steam} + E_{flue\ gas} \tag{14}$$

where, $E_{hot\ gas}$ and E_{water} represent the energy contents of input, E_{steam} and $E_{flue\ gas}$ represent the energy contents of output streams, respectively.

Exergy balance for heat exhanger equation:

$$E_{xhot\ gas} + Ex_{water} = Ex_{steam} + Ex_{flue\ gas} + I \tag{15}$$

where, $Ex_{hot\ gas}$ and Ex_{water} represent the exergy contents of input while Ex_{steam} and $Ex_{flue\ gas}$ represent the exergy contents of output streams, whereas I represent destruction.

The expressions for energy (η) based on the first law of thermodynamics and exergy (Ψ) efficiencies based on second law of thermodynamics for a combustor, heat exchanger, and overall boiler are given below:

For combustion chamber:

$$\eta_c = \frac{E_{hot\ gas}}{E_{biomass}} \tag{16}$$

$$\Psi = \frac{Ex_{hot\ gas}}{Ex_{biomass}} \tag{17}$$

For heat exchanger:

$$\eta_h = \frac{E_{steam} - E_{water}}{E_{hot\ gas} - E_{flue\ gas}} \tag{18}$$

$$\Psi_h == \frac{Ex_{steam} - Ex_{water}}{Ex_{hot\ gas} - Ex_{flue\ gas}} \tag{19}$$

Overall boiler:

$$\eta_O = \frac{E_{steam} - E_{water}}{E_{biomass}} \tag{20}$$

$$\Psi_O == \frac{Ex_{steam} - Ex_{water}}{Ex_{biomass}} \tag{21}$$

Table 1. Specific enthalpy, entropy and standard chemical exergy of gaseous constituents

Component	h_0 ($kJkg^{-1}$)	s_O ($kJkg^{-1}$·K)	e_{ich} ($kJkg^{-1}$)
N_2	0	6.832	23.79
O_2	0	6.408	123.95
H_2O (g)	–12,682	10.485	526.63
CO	–4,895	7.049	9,820.17
CO_2	–8,963	4.856	451.43
H_2	0	64.644	116,831.68
NO	–3,669	7.284	332.07
NO_2	–6,345	6.518	431.17

4. RESULTS AND DISCUSSION

The simulation for boiler was conducted in Aspen Plus®, and the resulting was employed for energy and exergy calculations. The Aspen Plus® simulation was performed with the temperature for biomass decomposition set at 400°C, while maintaining a constant operating pressure of 1 atm. Various substance parameters were carefully considered, such as air at 13.94 kgh^{-1} and 30°C, biomass at 1.65 kgh^{-1} and 30°C, hot gas at 15.59 kgh^{-1} and 1,885°C, water at 10 kgh^{-1} and 100°C, steam at 10 kgh^{-1} and 185°C and flue gas at 15.59 kgh^{-1} and 212.57°C. Tables 2 and 3 present the energy and exergy balance for both the combustion chamber and heat exchanger in the boiler system, detailing the input and output of energy within these components. Table 4 provides a comprehensive summary of the energy and exergy balances for the entire boiler system, offering an overall view of its performance. The tables collectively offer a detailed understanding of the energy and exergy efficiencies of the boiler system.

Table 2: Energy balance in combustion and heat exchanger for different biomass sample

Sample	Combustion chamber energy balance		Heat exchanger energy balance	
	Energy in (kW)	Energy out (kW)	Energy in (kW)	Energy out (kW)
1	9.78	8.2024	9.3667	8.5294
2	9.70	8.1787	9.3431	8.5269
3	10.10	8.2108	9.3751	8.5283
4	9.81	8.2044	9.3688	8.5287
5	9.67	8.0621	9.2265	8.5246

(*Continued on next page*)

Table 2 (*Continued*)

Sample	Combustion chamber energy balance		Heat exchanger energy balance	
	Energy in (kW)	Energy out (kW)	Energy in (kW)	Energy out (kW)
6	11.10	8.2131	9.3775	8.5252
7	9.56	8.1841	9.3485	8.5279
8	9.70	8.2043	9.3686	8.5265
9	10.40	8.2147	9.379	8.5279
10	10.20	8.1520	9.3164	8.5231
11	10.80	8.1477	9.3121	8.5222
12	10.50	8.1952	9.3595	8.5231
13	10.50	8.2386	9.4029	8.5274

Table 3: Exergy balance in combustion and heat exchanger for different biomass sample

Sample	Combustion chamber exergy balance			Heat exchanger exergy balance		
	Exergy in (kW)	Exergy out (kW)	Exergy destruction (kW)	Exergy in (kW)	Exergy out (kW)	Exergy destruction (kW)
1	8.8295	5.8596	2.96990	5.9420	2.7857	3.1563
2	8.8194	5.8442	2.97520	5.9266	2.7822	3.1443
3	9.0822	5.8684	3.21380	5.9508	2.7815	3.1692
4	8.8727	5.8625	3.01010	5.9449	2.7832	3.1617
5	9.0334	5.7530	3.28030	5.8354	2.7875	3.0478
6	10.1637	5.8782	4.28540	5.9606	2.7526	3.2080
7	8.6349	5.8466	2.78831	5.9290	2.7853	3.1437
8	8.7316	5.8667	2.86496	5.9490	2.7721	3.1770
9	9.3828	5.8728	3.51002	5.9552	2.7774	3.1777
10	9.1762	5.8293	3.34689	5.9117	2.7721	3.1396
11	9.9002	5.8281	4.07205	5.9105	2.7654	3.1451
12	9.3769	5.8665	3.51046	5.9489	2.7528	3.1961
13	9.5594	5.8949	3.66458	5.9773	2.7602	3.2171

4.1 Energy and Exergy Efficiency

The study presents a similar between energy and exergy efficiency, as seen in Table 4. It shows that energy efficiency is higher than exergy efficiency for both combustion and heat exchanger, as well as for the entire system. The overall energy and exergy efficiencies varied from 81.96% to 68.58% and 23.75% to 20.42%, respectively. Specifically, for the combustion chamber, energy efficiency ranged from 100% to 85.79%, while the exergy efficiency varied from 61.19% to 53.88%, respectively. For heat exchanger, the energy and exergy efficiency varied from 90.34% to 88.23% and 42.23% to 40.92%, respectively.

Table 4: Comparison of energy and exergy in combustion, heat exchanger and overall boiler

Sample	Combustion chamber energy (%)	Heat exchanger energy (%)	Overall boiler energy (%)	Combustion chamber exergy (%)	Heat exchanger exergy (%)	Overall boiler exergy (%)
1	99.6495	88.6899	79.7627	61.1948	41.3880	23.2761
2	100.000	88.9437	80.5909	61.0984	41.4800	23.3006
3	96.5397	88.5765	77.1946	59.7104	41.2883	22.6775
4	99.3015	88.6559	79.4643	60.9509	41.3461	23.1716
5	99.3816	90.3432	80.9324	58.8289	42.2385	22.7909
6	85.7916	88.5114	68.5807	53.8819	40.9940	20.4295
7	100.000	88.8909	81.9639	62.3259	41.4847	23.7589
8	100.000	88.6322	80.5617	61.9015	41.2294	23.5165
9	93.2276	88.5249	74.5110	57.9823	41.2235	22.0045
10	94.5550	89.2201	76.1523	58.7515	41.5162	22.4627
11	87.8520	89.2617	70.7914	54.7450	41.4739	20.9352
12	91.2932	88.7005	73.1383	57.9535	41.0843	22.0173
13	91.9036	88.2335	73.2393	57.2027	40.9250	21.6274

4.2 Environmental Sustainability

The higher energy efficiency observed during the combustion process suggests that a significant portion of the energy generated is effectively utilised, contributing positively to environmental sustainability by reducing energy waste. Moreover, the enhanced efficiency in energy recovery within the heat exchanger, as seen in Figures 4 and 5, underscores the system's role in optimising resource utilisation, promoting renewable energy goals and reducing reliance on non-renewable sources. While no direct environmental measurements were made, these efficiency improvements could potentially lead to lower greenhouse gas emissions, reinforcing the study's relevance in addressing sustainability challenges.

As shown in Figure 4, the energy efficiency during combustion surpasses exergy efficiency, indicating that a significant portion of the energy generated is effectively utilised, and enhancing overall sustainability. Furthermore, Figure 5 illustrates that the energy efficiency of the heat exchanger is consistently higher than its exergy efficiency, which suggests optimised energy recovery within the system. Finally, Figure 6 confirms that the overall energy efficiency of the boiler exceeds its exergy efficiency, highlighting the effectiveness of this biomass utilisation strategy in promoting renewable energy goals. This combined evidence underscores the importance of enhancing waste management practices through efficient energy conversion, reinforcing the study's commitment to sustainability.

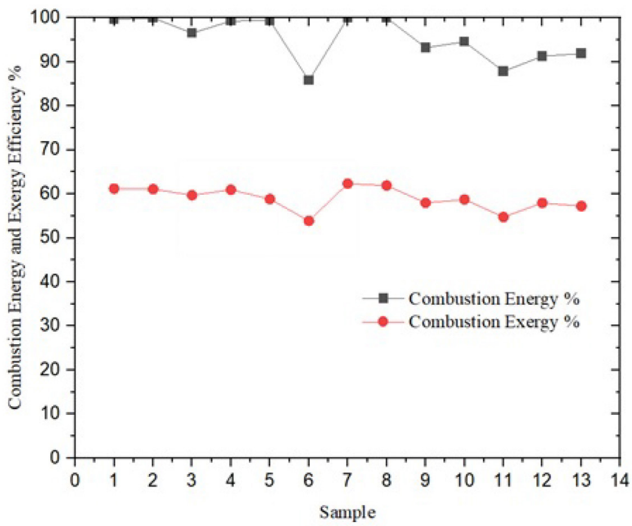

Figure 4: Combustion energy and exergy efficiency for different biomass samples.

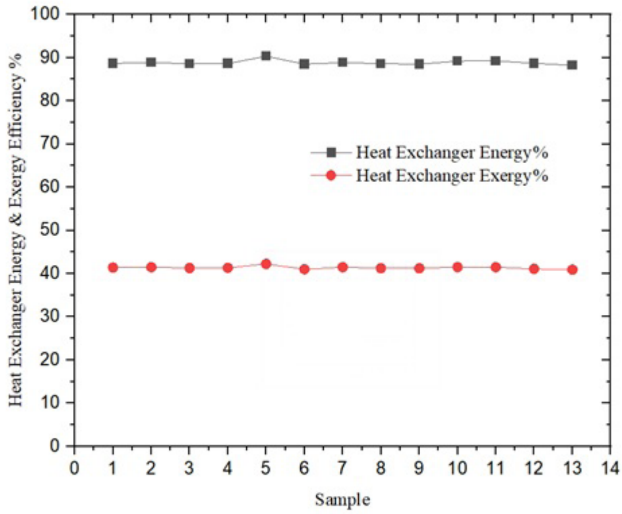

Figure 5: Heat exchanger energy and exergy efficiency for different biomass samples.

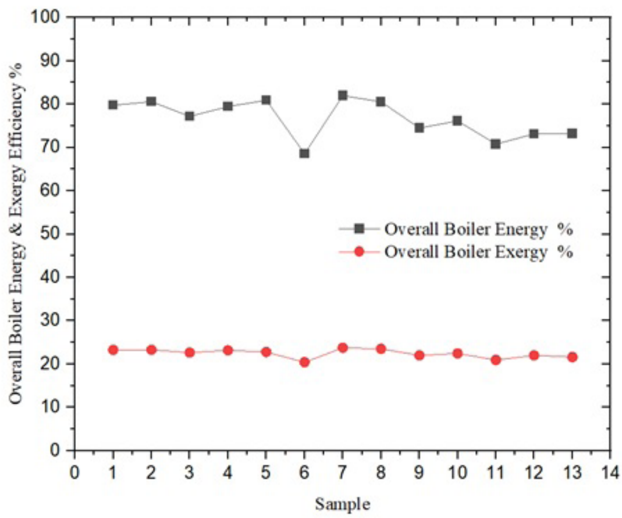

Figure 6: Overall boiler energy and exergy efficiency for different biomass samples.

4.3 AFR Analysis

Figures 7 and 8 demonstrate that increasing the AFR enhances both combustion energy and exergy efficiencies. Specifically, energy efficiency peaks at an AFR of 8.5 for certain biomass types and at 9.5 for all biomass types. This finding highlights the significance of optimising AFR in achieving improved boiler performance. The correlation between increased airflow and higher exergy efficiency emphasises the need for precise control in combustion processes to maximise efficiency.

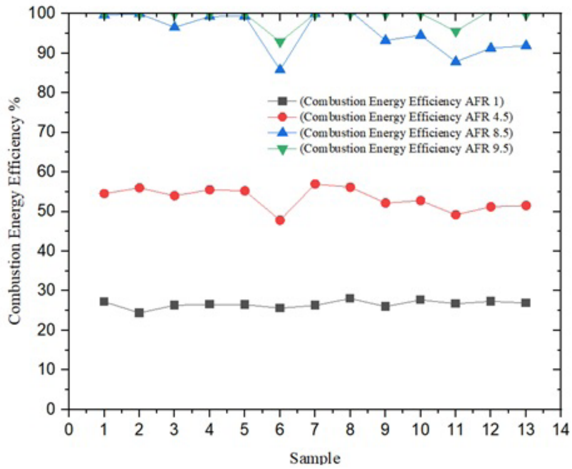

Figure 7: Combustion energy efficiency for different biomass samples at different AFR.

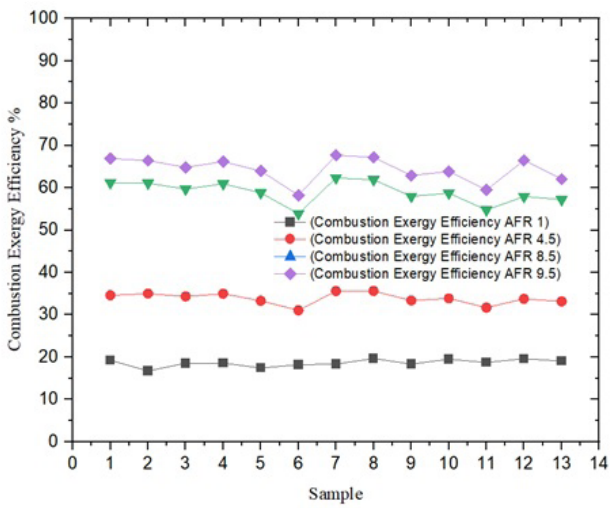

Figure 8: Combustion exergy efficiency for different biomass samples at different AFR.

4.4 Comparison with Other Studies

Table 5 compares the energy and exergy efficiencies of this biomass boiler with those from other studies. Given the lower heating value of biomass compared to natural gas and other fossil fuels, the energy and exergy efficiency figures for this biomass boiler are understandably lower. However, the results are consistent with findings from similar studies, highlighting that biomass combustion, despite slightly lower efficiencies for some sample, plays a significant role in transitioning to renewable energy systems. This comparison could be expanded to further differentiate this study in terms of methodology, efficiency ranges, or specific findings, offering a broader context for understanding the performance of biomass boilers.

Table 5: Energy and exergy efficiency data from multiple boiler studies

Study	Boiler	Energy efficiency (%)	Exergy efficiency (%)
Marc Compton (2018)	Biomass	76	24
	NG1	85	27
	NG2	78	25
	NG3	85	27
Oladiran and Meyer (2007)	Industry	83	16
Saidur (2010)	Gasoline	72.46	24.89
Present work	Biomass sample 1	79.7627	23.2761
	Biomass sample 2	80.5909	23.3006
	Biomass sample 3	77.1946	22.6775
	Biomass sample 4	79.4643	23.1716
	Biomass sample 5	80.9324	22.7909
	Biomass sample 6	68.5807	20.4295
	Biomass sample 7	81.9639	23.7589
	Biomass sample 8	80.5617	23.5165
	Biomass sample 9	74.5110	22.0045
	Biomass sample 10	76.1523	22.4627
	Biomass sample 11	70.7914	20.9352
	Biomass sample 12	73.1383	22.0173
	Biomass sample 13	73.2393	21.6274

4.5 Limitations

While the use of Aspen Plus® for biomass combustion analysis provides valuable insights into the design of combustion processes, it comes with several limitations. Simulations, including those conducted with Aspen Plus®, operate under ideal conditions and often do not account for critical factors such as incomplete combustion and mechanical inefficiencies within boiler systems. These omissions can significantly influence the accuracy of efficiency results. Moreover, capturing all physical phenomena and incorporating losses in simulations can complicate the modelling process, making it challenging to achieve reliable outcomes. The current modelling approach relies on an equilibrium framework, which, while widely used, may not fully represent the complexities of real-world scenarios. To overcome these limitations, future research should focus on enhancing simulation accuracy by integrating comprehensive validation efforts and exploring the inclusion of kinetic parameters in the modelling process. This will facilitate a more practical understanding of biomass system performance and contribute to optimising biomass energy technologies.

5. CONCLUSION

In this study, a simulation of a biomass combustion boiler using 13 distinct biomass sources from Malaysia was conducted, accompanied by energy and exergy analyses. The findings reveal significant potential for high energy and exergy performance across various biomass types. The energy efficiency ranges from 68.58%–81.96%, with an average of 76.68%, indicating strong performance. Exergy efficiency ranges from 20.42%–23.75%. While averages at 22.45%. The combustion chamber is identified as the component with the highest exergy destruction rate, followed by the heat exchangers. Comparative analysis with other studies shows consistent results, validating the reliability of the findings.

A parameter study on AFRs demonstrated that energy efficiency reaches a maximum at a ratio of 8.5 for some biomass types. For all samples, the maximum energy efficiency is achieved at a ratio of 9.5, beyond which no further improvement is observed.

Overall, the results support the use of Malaysian biomass as a sustainable and effective fuel for biomass combustion boilers. The better use of biomass as energy in Malaysia and around the world is critical for reducing dependence on fossil fuels and tackling waste management issues. By converting palm oil waste into energy, biomass usage not only reduces landfill waste but also turns it into a profitable resource. This process enhances system efficiency and supports economic viability, aligning with global sustainability goals. Thus, biomass energy emerges as a vital player in the transition to renewable energy sources.

5.1 Future Research

To further develop the use of biomass energy in Malaysia and globally, future research priorities must include investigating ways to reduce losses in process units and optimising combustion conditions to improve overall system efficiency and environmental impact. First, experimental validation of simulation results is essential to confirm the accuracy of models and assumptions used in combustion analysis. Finally, future studies should investigate the integration of kinetic parameters into existing models to better represent real-world combustion conditions. This comprehensive approach will facilitate a more practical understanding of biomass system performance and support the transition to renewable energy solutions.

5.2 Policy and Industry Relevance

The study's findings show that Malaysian biomass, particularly palm oil waste, is nearly as efficient as fossil fuels, making it an attractive and feasible substitute option in a variety of industries. It provides financial incentives for industries to adopt modern biomass technologies because biomass, often derived from waste, presents a sustainable alternative to conventional fuels. Setting high efficiency and emission regulations would help stakeholders adopt sustainable practices. Partnership among government, industry and academic institutions will encourage innovation in biomass energy utilisation, ensuring that the outcomes of this research lead to the optimisation of biomass boilers and the transition to sustainable energy sources, resulting in practical, real-world applications that benefit both the environment and the economy.

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