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Optimization of Biomass Gasification in a Dual Fluidized Bed Reactor: A Modeling Approach Using Aspen Plus

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Abstract. The growing demand for sustainable energy has positioned biomass gasification as a promising thermochemical conversion technology, particularly in Dual Fluidized Bed (DFB) reactors, which are known for producing high-quality syngas with low tar and nitrogen content. This study presents the development and validation of a biomass gasification model using Aspen Plus, integrating thermodynamic and kinetic parameters to simulate the conversion of three biomass types: BBJP (solid refuse-derived fuel), sawdust, and wood chips. The model's accuracy was validated against experimental data for both Single Fluidized Bed (SFB) and DFB configurations, demonstrating strong accuracy, with R^2 values exceeding 90% for key gas components. The simulation results indicated that the DFB configuration significantly enhanced hydrogen (H_2) production, with the highest yield achieved using BBJP (59.84 mol%) at approximately 750°C, followed by sawdust (56.7 mol%) and wood chips (56.08 mol%). Additionally, the study found that a steam-to-biomass ratio of 0.7 optimizes H_2 production, beyond which performance decreases due to syngas dilution. Energy analysis revealed the DFB system produced higher Lower Heating Values (LHV) than the SFB system, with sawdust yielding 23.07 MJ/kg, indicating strong potential for practical application. The model provides valuable insights into optimizing biomass gasification processes, advancing renewable energy technologies, and supporting sustainable power generation initiatives, particularly in Indonesia.

Keywords: *Biomass Gasification, Dual Fluidized Bed, Aspen Plus, Renewable Energy, Hydrogen*

1 Introduction

The global transition toward a more sustainable energy system has become a top priority in efforts to mitigate climate change and reduce dependence on fossil fuels. In this context, biomass as a renewable energy source offers significant potential due to its carbon-neutral nature and abundant availability [1]. According to the latest report from [2], bioenergy accounted for approximately 55% of total global renewable energy consumption in 2022, with projections indicating substantial growth through 2030.

Biomass is a renewable energy source derived from organic materials such as plants and organic waste. In steam power plants (PLTU), various types of biomass have been used as alternative fuels or co-fired with coal. According to [3], biomass characteristics such as calorific value, moisture content, and chemical composition significantly influence performance in gasification and combustion processes.

Among the various existing gasification technologies, the Dual Fluidized Bed (DFB) reactor has gained particular attention due to its ability to produce high-quality syngas with low nitrogen content. The DFB system consists of two interconnected reactors: a gasification reactor and a combustion reactor. The separation of the gasification and combustion zones enables the production of a hydrogen-rich syngas (H_2-rich gas) with higher calorific value and lower tar content than conventional gasifiers. Additionally, bed material circulation between the two reactors facilitates efficient heat transfer, reducing the need for external energy input [4].

Although biomass gasification technology in DFB reactors shows promising potential, the optimization and scale-up of this process still face several challenges. The complex interactions among various physical and chemical phenomena occurring in the reactor, including chemical reactions, heat and mass transfer, and fluidization hydrodynamics, make it difficult to fully understand and predict process performance. Furthermore, the variability in biomass characteristics and the process's sensitivity to operating conditions add another layer of complexity in designing and operating an efficient gasification system [5]. Unlike previous works, this study incorporates Indonesian-specific biomass (BBJP) and compares DFB vs SFB using real experimental data, providing a contextualized and validated approach for national energy strategies.

Biomass gasification is one of the most promising thermochemical conversion technologies for harnessing bioenergy potential. This process involves converting biomass into a synthetic gas (syngas) mixture primarily composed of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), and carbon dioxide (CO_2) under limited oxygen conditions at high temperatures. The resulting syngas can be utilized for various applications, including power generation, synthetic fuel production, and chemical synthesis [6].

The modeling of biomass gasification integrated with other energy systems, such as fuel cells or combined gas cycles, offers the potential to enhance overall efficiency and reduce emissions. However, evaluating the performance of such integrated systems requires accurate and flexible simulation models [7]. Therefore, this thesis aims to develop the optimization of the biomass gasification process in a double bed fluidized reactor model using Aspen Plus, incorporating both thermodynamic and kinetic aspects of the reactor. We validated the model using experimental data and applied it for sensitivity analysis, optimization, and system integration evaluation. The results of this study are expected to contribute significantly to the understanding and advancement of biomass gasification technology and support its large-scale implementation as part of the transition toward a more sustainable energy system. This research not only focuses on technical and operational aspects but also considers the environmental impacts of using biomass as an alternative energy source. Through this approach, it is expected that PLTU Paiton and PLTU Tenayan can serve as models for developing efficient and sustainable biomass-based power plants in Indonesia.

2 Methodology

2.1 Data Collection

In this study, a simulation was carried out using Aspen Plus to evaluate the thermochemical conversion performance of three different types of biomass feedstocks: BBJP (solid refuse-derived fuel), Sawdust, and Wood Chip. These feedstocks were selected due to their availability and varying fuel characteristics, which are expected to influence the efficiency and product yield in the conversion process.

The fuel properties of the biomass materials, based on proximate and ultimate analyses (on a dry basis), are summarized in Table 1. The proximate analysis includes ash content, volatile matter (VM), and fixed carbon (FC). In contrast, the ultimate analysis covers the elemental composition, such as carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O). These parameters are essential inputs for simulation in Aspen Plus, particularly for defining the feedstock specifications and estimating the syngas composition, heat balance, and overall conversion efficiency.

In simulation, the developed gasification model will be validated using two configurations: the Single Fluidized Bed (SFB) and the Dual Fluidized Bed (DFB) gasification systems. These validation steps are essential to ensure that the simulation results align with expected reactor behavior under different operating conditions, and to assess the performance, syngas composition, and carbon conversion efficiency for each biomass type under both gasification schemes.

Table 1 Fuel properties of various biomass materials

Feedstock	Proximate analysis Ash (%)	VM (%)	FC (%)	C (%)	Ultimate analysis H (%)	N (%)	S (%)	O (%)
BBJP	36.55	52.70	10.75	31.67	3.92	1.69	0.34	25.83
Sawdust	2.36	80.34	17.30	52.58	5.81	0.48	0.11	38.66
Wood Chip	1.38	80.91	17.71	50.14	5.81	0.07	0.07	42.41

2.2 Assumptions

The following assumptions are made based on the application of Aspen Plus software:

1. The combustor and the gasifier were operated under a steady state, and the reactions were reached using the GIBBS Reactor
2. Char is 100 % carbon, and ash is inert.
3. The properties method is Peng-Robinson, which is suitable for high temperatures, such as gasification
4. The product gases of biomass gasification were H2, CO, CO2, CH4, H2O, N2, H2S, NH3, COS, and SO2; tar was not taken into account in the simulation
5. Air consists of 79 % nitrogen and 21 % oxygen on a molar basis.
6. The system operates at atmospheric pressure, and all pressure drops are neglected

2.3 Process Modelling Simulation

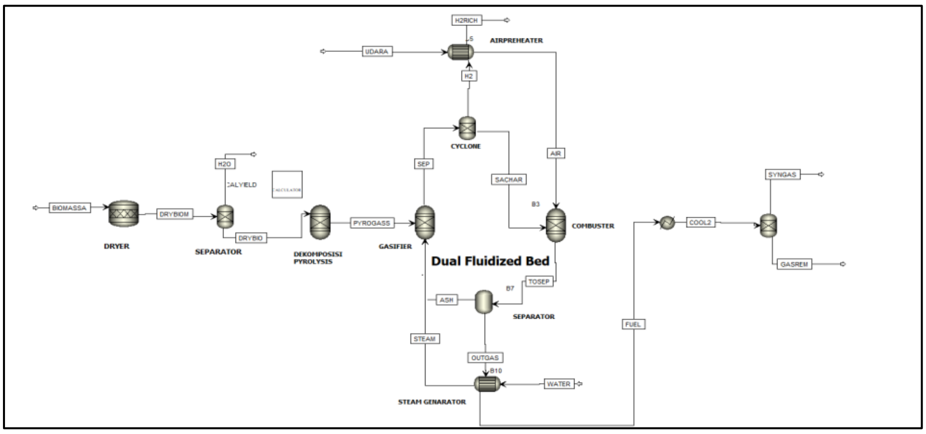

Figure 1 Flowsheet simulation of a biomass gasification model using a Dual Fluidized Bed (DFB)

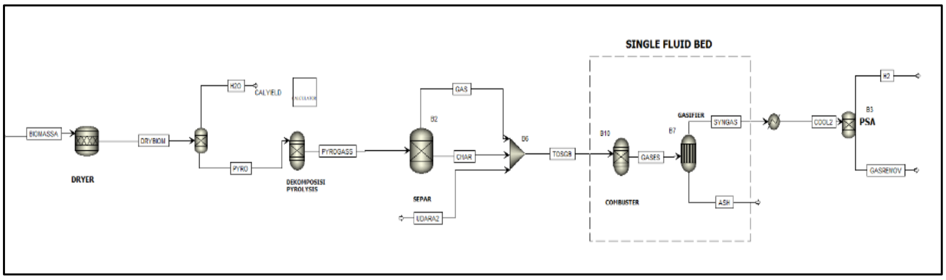

Figure 2 Flowsheet simulation of a biomass gasification model using a Single Fluidized Bed (SFB)

2.4 Process Description

Single Fluidized Bed (SFB) is a gasification system that utilizes a single reactor in which biomass is converted into gas with the assistance of air or steam. This system is simpler in design and operation, making it suitable for laboratory studies or small to medium-scale applications. However, this configuration tends to produce more char due to the lack of separation between the combustion and gasification zones. Generally, it has a lower conversion efficiency compared to dual systems. Adding steam as a gasifying agent can enhance the hydrogen (H_2) content in the resulting syngas.

In contrast, the Dual Fluidized Bed (DFB) system employs two separate reactors: one for biomass gasification and the other for the combustion of auxiliary fuel. This configuration prevents the direct mixing of air into the main gasification reactor, resulting in syngas with higher H_2 content and lower char production than the SFB system.

The SFB system is more appropriate for simple applications with minimal infrastructure requirements. In contrast, the DFB system offers superior syngas quality and higher efficiency, albeit requiring a more complex design and operation. The choice between gasification methods should be tailored to specific needs, including target H_2 yield, biomass feedstock type, and operation scale.

Biomass is fed into the gasifier, which undergoes thermal decomposition in the presence of steam and air gasifying agents. The gasifier operates in a relatively oxygen-deficient environment, facilitating the production of a hydrogen-rich syngas (H_2-rich gas) through a series of reactions such as drying, pyrolysis, reduction, and reforming. Steam acts as the leading gasifying agent, promoting hydrogen production, while a limited amount of air may be used to maintain the temperature inside the reactor.

The solid residues, primarily char, are transported from the gasifier to the combustor. The char is entirely burned with air in the combustor, generating the necessary thermal energy to sustain the gasification reactions. This heat is then transferred back to the gasifier, usually through circulating bed material or indirect contact, allowing continuous operation without introducing nitrogen into the syngas stream (since air is not directly used in the gasifier).

Although tar formation is not modeled in this simulation due to software limitations, it remains a critical issue in biomass gasification processes. Tar consists of complex hydrocarbon compounds that can lead to operational problems such as clogging, corrosion, and reduced system efficiency. In Single Fluidized Bed (SFB) systems, all reactions occur within a single reactor, resulting in less optimal temperature control and consequently higher tar formation. In contrast, Dual Fluidized Bed (DFB) systems separate the combustion and gasification zones, allowing for more stable temperatures and effective tar cracking. Studies such as [8]. Report that tar concentrations in SFB systems can reach 10–20 g/Nm^3, whereas DFB systems can reduce tar levels to below 5 g/Nm^3 [9]. Therefore, future models should incorporate tar yield prediction and mitigation strategies, such as catalysts, high-temperature operation, and enhanced reactor designs, to improve model accuracy and reflect real operating conditions.

The flue gas produced in the combustor is released through the exhaust system. At the same time, the clean syngas exits the gasifier and can be utilized for downstream applications such as power generation, hydrogen recovery, or chemical synthesis.

3 Results and Discussion

3.1 Model Validation

Experimental data from a single fluidized bed (SFB) gasification study conducted by [10] using Prosopis Juliflora as the feedstock were adopted to validate the model developed in this study. The results of the simulation model were compared with the experimental data from previous work. The composition of the product gases from both the simulation model and the experiment is presented in Figure 3, showing a good agreement between the model predictions and the experimental observations.

Technically, the graph illustrates the relationship between gasification temperature (800–1000 °C) and the mass fractions of the three main product gas components: H_2, CO, and CH_4. The graphs for H_2 and CO show an increasing trend in mass fraction with rising temperature. This indicates that reforming and water-gas shift reactions become more dominant at higher temperatures, promoting the production of H_2 and CO. In contrast, the graph for CH_4 shows a decreasing mass fraction as the temperature increases, suggesting that methane cracking and reforming reactions become more significant at elevated temperatures.

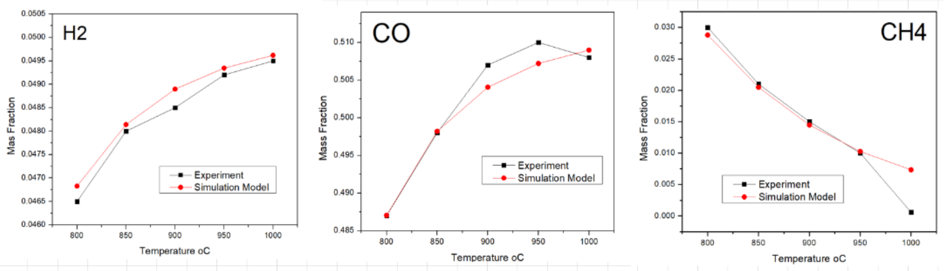

Figure 3 Validation of modelling simulation Single Fluidized Bed (SFB)

The close match between the simulation model curves and experimental data points supports the model validation, which is quantitatively confirmed by high coefficients of determination (R^2): 94.29% for H_2, 95.20% for CO, and 90.32% for CH_4. These values indicate that the model accurately predicts the behavior of the gasification process, which will later be important for real-world applications.

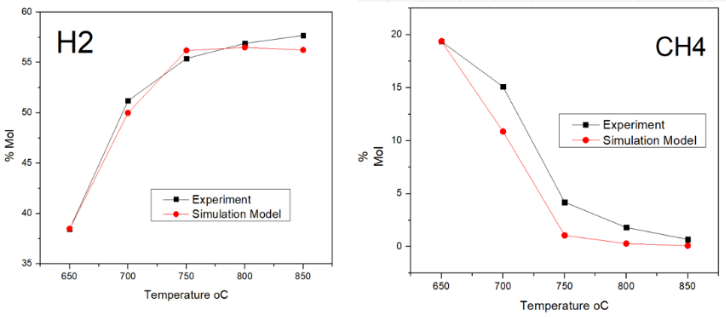

Figure 4 Validation of modelling simulation Dual Fluidized Bed (DFB)

Experimental data from a Dual fluidized bed (DFB) gasification study by [11], using straw as feedstock, was adopted to validate the simulation model developed in this work. The simulation results were extracted and compared with the experimental data reported in the literature. The product gas compositions, specifically for CH_4 and H_2, are illustrated in Figure 4.

As shown in the figure, the simulated molar fractions of CH_4 and H_2 as functions of temperature exhibit a trend that closely aligns with the experimental data. For CH_4, the concentration decreases significantly with increasing temperature. This is technically due to the endothermic nature of methane steam reforming

$$(CH_4 + H_2O \rightarrow CO + 3H_2) \qquad (1)$$

which becomes more favorable at higher temperatures, thus consuming more CH_4 as temperature increases.

In contrast, the concentration of H_2 increases with temperature, indicating the dominance of both steam reforming and water-gas shift reactions

$$(CO + H_2O \rightarrow CO_2 + H_2) \qquad (2)$$

under thermal enhancement. These reactions not only produce more H_2 but also reduce CO content, shifting the equilibrium in favor of hydrogen generation. Increasing H_2 yield with temperature is a common indicator of effective gas-phase reforming in biomass gasification systems.

The simulation model demonstrated strong accuracy from the comparison, with coefficients of determination (R^2) of 91.09% for CH_4 and 97.49% for H_2. These values reflect a strong statistical correlation between the simulated outputs and the experimental measurements, confirming that the model can accurately replicate real gasification behavior under varying thermal conditions.

The successful validation implies that the developed model can reliably simulate other biomass feedstocks or explore parameter sensitivities such as steam-to-biomass ratio, pressure effects, or reactor configuration. This makes it a valuable predictive tool for optimizing and scaling up biomass gasification processes in future energy conversion systems.

3.2 Effects of Gasification Temperature

Operating temperature is one of the key parameters in the performance of a Dual Fluidized Bed (DFB) reactor, especially in the hydrogen (H_2) production process. The appropriate temperature can enhance reaction rates, feedstock conversion, and the distribution of the resulting product gases. In a DFB system, the operating temperature influences key reactions such as gasification, reforming, and cracking, determining the amount of hydrogen that can be produced.

This study used various types of biomass feedstock, namely BBJP (solid refuse-derived fuel), sawdust, and wood chips, to evaluate the effect of temperature on

H_2 yield. Each type of biomass has different proximate and ultimate compositions, such as moisture content, volatile matter, fixed carbon, ash content, and main elemental components including carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S).

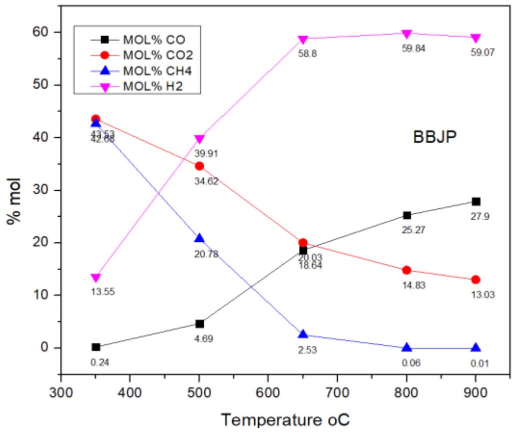

Figure 5 Effect of temperature on H_2 yield from BBJP

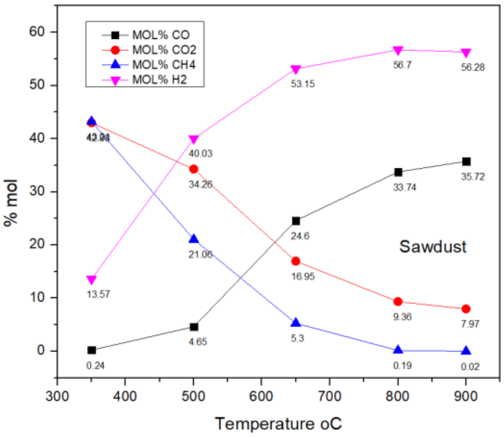

Figure 6 Effect of temperature on H_2 yield from sawdust

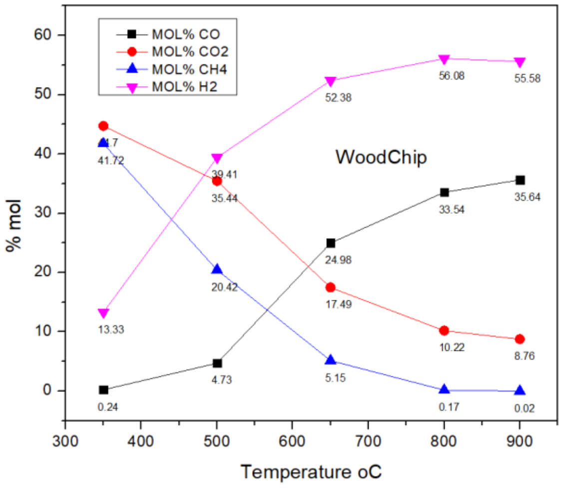

Figure 7 Effect of temperature on H_2 yield from woodchip

These compositional differences affect the reactivity of the biomass in the reactor and the resulting hydrogen production. Additionally, selecting the optimal temperature presents a particular challenge, as excessively high temperatures can increase the formation of by-product gases such as carbon monoxide (CO) and carbon dioxide (CO_2), which may reduce the purity and yield of H_2. Therefore, analyzing the impact of operating temperature on each feedstock is crucial for optimizing process efficiency and hydrogen output in a dual fluidized bed reactor system.

The effect of temperature on the syngas composition produced from three types of biomasses, BBJP, sawdust, and wood chips, in a Dual Fluidized Bed (DFB) reactor system. Increasing the temperature from 350°C to approximately 750–800°C significantly enhances the hydrogen (H_2) yield for all three biomass types. This increase is primarily attributed to the dominance of endothermic reactions, such as steam reforming and the water-gas shift reaction, which play a crucial role in promoting H_2 formation. Steam reforming converts methane (CH_4) into H_2 and CO, while the water-gas shift reaction transforms CO and steam into additional H_2 and CO_2. The observed decrease in CH_4 and CO_2 concentrations at higher temperatures, along with the increase in H_2, supports the involvement of these components in hydrogen-producing reactions.

The choice of gasifying agent also significantly influences the composition of the product gas. When air is used as the gasifying agent, the nitrogen content in the syngas becomes high, which directly dilutes the H_2 concentration since nitrogen is inert and does not participate in the fuel-forming reactions. In contrast, using steam as the gasifying agent enhances reforming and water-gas shift reactions, resulting in a higher H_2/CO ratio, more favorable for pure hydrogen production. An increased partial pressure of steam can further accelerate the conversion of CO to H_2, leading to a hydrogen-rich syngas product [12].

On the other hand, the characteristics of the biomass feedstock play a vital role in the efficiency and output of the gasification process. Proximate and ultimate properties such as volatile matter (VM), fixed carbon (FC), ash content, moisture, and elemental composition (C, H, O, N, and S) determine the biomass reactivity in the reactor. Biomass with high VM content tends to produce more gas during the initial pyrolysis and gasification stages; however, excessively high VM can increase tar formation, which disrupts the process [13]. High fixed carbon is essential for sustaining the gasification reactions at elevated temperatures, especially for forming H_2 and CO [14]. Therefore, to maximize syngas production with high H_2 and CO content, biomass with high VM, FC, carbon, and hydrogen content, and low moisture and ash levels is ideal [15].

According to the graph results, BBJP produces the highest H_2 yield, 59.84 mol%, at around 750°C, indicating that its chemical properties strongly support hydrogen-producing reactions. Sawdust and wood chips exhibit a similar trend, with peak H_2 yields of approximately 56.7 mol% and 56.08 mol%, respectively.

However, beyond 800°C, the H_2 yield begins to plateau or decline, likely due to secondary reactions or shifts in chemical equilibrium. Meanwhile, CO yield continues to increase to around 900°C before declining, suggesting enhanced activation of the water-gas shift reaction at elevated temperatures.

In conclusion, temperature increases and the selection of gasifying agent and biomass type significantly affect hydrogen production efficiency and syngas yield. Optimizing these three factors, temperature, gasifying agent, and feedstock characteristics, is key to enhancing the performance of DFB gasification systems for high-quality syngas production.

3.3 Effect of Steam-to-Biomass Ratio (S/B)

In this study, biomass was fed at 1000 kg/h, with air and steam at 100 kg/h and 700 kg/h, respectively. The results show that increasing temperature enhances H_2 yield, consistent with previous studies highlighting the importance of steam in promoting water-gas shift and reforming reactions. A high steam-to-air ratio favored hydrogen production, aligning with findings by [16] and [17], which reported significant H_2 yield improvements under steam-rich conditions. In contrast, excessive air increases CO and CO_2 due to dominant oxidation reactions, reducing H_2 generation efficiency [18].

Figure 8 illustrates that increasing the steam-to-biomass (S/B) ratio from 0.5 to 0.7 significantly boosts H_2 yield. Beyond 0.7 (i.e., 0.8–0.9), the gain diminishes due to syngas dilution and excess CO_2 formation. CO_2 levels decrease to an S/B ratio of 0.7, while CH_4 consistently declines with temperature due to reforming.

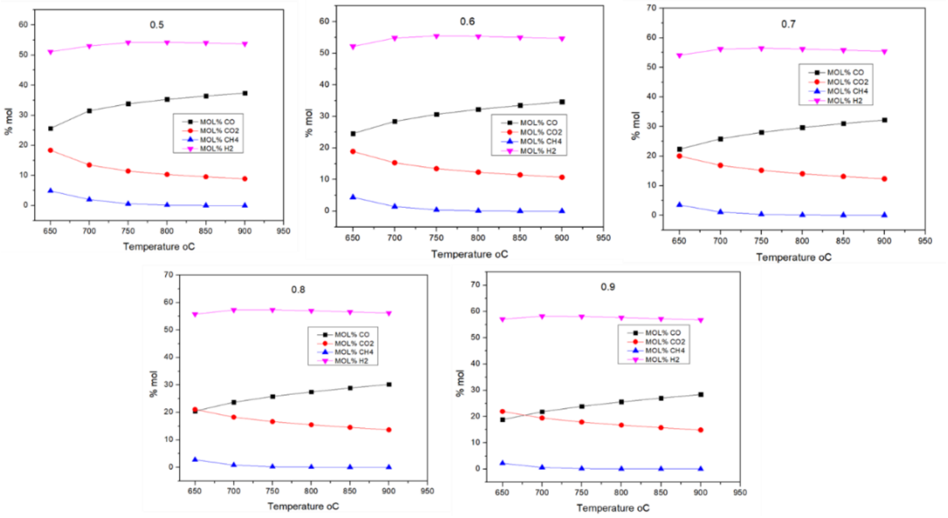

Figure 8 Effect of steam-to-biomass ratio

As the steam/biomass ratio increases from 0.5 to 0.7, the H_2 yield significantly improves. This enhancement is attributed to the intensified steam reforming and water-gas shift reactions, which are favored under high steam availability and elevated temperatures. At a ratio of 0.7, the hydrogen yield remains consistently high across the temperature range, confirming this ratio as optimal among the tested conditions. CO_2 content decreases as the steam ratio increases to 0.7, reflecting reduced oxidation reactions and increased hydrogen production. Meanwhile, CH_4 consistently decreases with temperature across all ratios, as it is consumed in endothermic reforming reactions. CO concentration shows a rising trend with temperature but remains lower than H_2 across all steam ratios, especially at 0.7 and above, where the water-gas shift reaction further converts CO into H_2.

In summary, the visual data reinforce the conclusion that a steam/biomass ratio of 0.7 offers the most balanced and efficient condition for maximizing hydrogen production without incurring dilution or reaction side effects. Ratios lower than 0.7 limit steam availability for reforming, while ratios above 0.7 introduce diminishing returns and potential inefficiencies.

Several previous studies have shown that the optimal ratio of gasifying agent to biomass depends heavily on the type of biomass and operating conditions. For example, [11] found that a steam/biomass ratio of 0.6–0.8 yielded optimal results for enhancing H_2 production in softwood gasification. This study used a steam/biomass ratio of 0.7, which falls within the optimal range for high hydrogen production.

On the other hand, [18] reported that using air as the leading gasifying agent (without steam) results in syngas with lower H_2 and higher CO content due to the dominance of partial oxidation reactions. This supports the advantage of this study's higher gasifying agent ratio for enhancing hydrogen yield.

3.4 Energy Analysis

The energy analysis was conducted to evaluate the energy potential of the product gas generated from each gasification process scheme. The primary parameter used is the Lower Heating Value (LHV), which indicates the amount of usable energy in the product gas, excluding the latent heat of water vapor.

Table 2 Energy analysis

Dual Fluid Bed			
Analysis	BBJP	Sawdust	Wood Chip
H_2 (mol%)	59.84	56.7	56.08
LHV Product (MJ/kg)	18.46	23.07	22.35
Single Fluid Bed			
Analysis	BBJP	Sawdust	Wood Chip
H_2 (mol%)	51.45	52.69	51.52
LHV Product (MJ/kg)	15.24	17.58	17.58

Based on Table 2, the LHV of the product gas for each feedstock is as follows: 18.46 MJ/kg for the BBJP scheme, 23.07 MJ/kg for Sawdust, and 22.35 MJ/kg for Wood Chip. Although BBJP yields a hydrogen-rich gas, it is energetically imbalanced due to the minimal contribution from CH_4 and CO. In other words, the energy quality of synthesis gas depends on a balanced composition of H_2, CO, and CH_4, rather than the dominance of a single component. BBJP may be more suitable for applications prioritizing hydrogen, such as fuel cells or further reforming, but is less advantageous for direct combustion or high-LHV co-firing applications.

4 Conclusions

Based on Aspen Plus modeling and simulation, biomass gasification in a Dual Fluidized Bed (DFB) reactor shows strong potential as an efficient and clean energy conversion technology. The model achieved high accuracy ($R^2 > 90\%$) when validated against experimental data for DFB and SFB systems. DFB outperformed SFB by producing syngas with higher hydrogen content due to the separation of combustion and gasification zones and the use of steam.

Among the tested feedstocks, BBJP (solid refuse-derived fuel) yielded the highest H_2 concentration (59.84 mol%) at 750°C, followed by sawdust (56.7 mol%) and wood chips (56.08 mol%). Hydrogen production increased with temperature up to an optimum point, driven by reforming and water-gas shift reactions. A steam-to-biomass ratio of 0.7 was identified as optimal, balancing H_2 yield and avoiding dilution. The DFB system also delivered higher syngas calorific value, with sawdust reaching 23.07 MJ/kg. These findings highlight that biomass selection, temperature control, and gasifying agent optimization are critical to maximizing gasification efficiency and syngas quality. A sensitivity analysis that considers economic parameters (fuel cost, hydrogen price) and environmental impacts (CO_2 emissions, ash disposal) should be conducted in future research. This would provide a more comprehensive evaluation of the technology's feasibility and support its large-scale implementation within Indonesia's energy systems. Overall, it significantly contributes to developing sustainable biomass-based energy systems and supports their broader implementation in power generation in Indonesia. Strategic implementation of biomass gasification in Indonesia should consider feedstock logistics, regional energy demands, and policy incentives to promote renewable-based distributed generation. Furthermore, the research can be further developed by incorporating additional factors, such as the environmental impact of biomass gasification, including NOx and SOx emissions.

References

[1] Steven S., Restiawaty, E., & Bindar, Y. (2021). Routes for energy and bio-silica production from rice husk: A comprehensive review and emerging prospect, Renewable and Sustainable Energy Reviews 149, No. Paper: 111329, 2021, https://doi.org/10.1016/j.rser.2021.111329.

[2] International Energy Agency. (2023). Renewables 2023: Analysis and forecast to 2028. IEA

[3] McKendry, P. (2002). Energy production from biomass (part 1): Overview of biomass. Bioresource Technology, 83(1), 37–46. https://doi.org/10.1016/S0960-8524(01)00118-3

[4] Ku, A. Y., Nguyen, T. H., Gung, B. W., & Tseng, H. H. (2019). A review of dual fluidized bed gasification systems for bioenergy applications. Energies, 12(8), 1500. https://doi.org/10.3390/en12081500

[5] Pissot, S., Dupont, C., Commandré, J. M., & Salvador, S. (2020). Modeling biomass gasification in dual fluidized bed gasifiers: A comprehensive review. Renewable and Sustainable Energy Reviews, 119, 109589. https://doi.org/10.1016/j.rser.2019.109589

[6] Molino, A., Chianese, S., & Musmarra, D. (2019). Biomass gasification technology: The state of the art overview. Journal of Energy Chemistry, 29, 1–29. https://doi.org/10.1016/j.jechem.2018.08.008

[7] Zhang, X., Sun, Q., Li, H., Wang, S., & Yan, J. (2020). A review of syngas-based solid oxide fuel cell systems integrated with biomass gasification. Renewable and Sustainable Energy Reviews, 119, 109589. https://doi.org/10.1016/j.rser.2019.109589

[8] Gil, J., Corella, J., Aznar, M. P., & Caballero, M. A. (1999). Biomass gasification in fluidized bed at pilot scale: tar production and characterization. *Energy & Fuels*, **13**(4), 702–709. https://doi.org/10.1021/ef980168b

[9] Abdelouahed, L., Authier, O., Mauviel, G., Corriou, J. P., Verdier, P., & Dufour, A. (2012). Detailed modeling of biomass gasification in dual

fluidized bed reactors under Aspen Plus. *Energy & Fuels*, **26**(6), 3840–3855. https://doi.org/10.1021/ef300427e

[10] Dhrioua, M., Zain, M., Chakroun, H., & Bouzaza, A. (2022). Experimental and modeling investigation of biomass gasification in a single fluidized bed reactor using Prosopis Juliflora as feedstock. Energy Conversion and Management, 255, 115352. https://doi.org/10.1016/j.enconman.2022.115352

[11] Shen, L., Gao, Y., & Xiao, J. (2008). Simulation of hydrogen production from biomass gasification in interconnected fluidized beds. Biomass and Bioenergy, 32(2), 120–127. https://doi.org/10.1016/j.biombioe.2007.08.003

[12] Zhao, Y., Wang, G., Liu, Q., & Shen, L. (2016). Steam gasification of biomass for hydrogen-rich gas production: A review. International Journal of Hydrogen Energy, 41(28), 12252–12265. https://doi.org/10.1016/j.ijhydene.2016.05.256

[13] Devi, L., Ptasinski, K. J., & Janssen, F. J. J. G. (2003). A review of the primary measures for tar elimination in biomass gasification processes. Biomass and Bioenergy, 24(2), 125–140. https://doi.org/10.1016/S0961-9534(02)00102-2

[14] Lv, P. M., Xiong, Z. H., Chang, J., Wu, C. Z., Chen, Y., & Zhu, J. X. (2004). An experimental study on biomass air–steam gasification in a fluidized bed. Bioresource Technology, 95(1), 95–101. https://doi.org/10.1016/j.biortech.2004.02.006

[15] Bridgwater, A. V. (2012). Review of fast pyrolysis of biomass and product upgrading. Biomass and Bioenergy, 38, 68–94. https://doi.org/10.1016/j.biombioe.2011.01.048

[16] Zhang, Y., Zhang, H., Liu, X., & Xu, Y. (2021). Effect of steam to biomass ratio on hydrogen production in biomass steam gasification. Energy, 229, 120653. https://doi.org/10.1016/j.energy.2021.120653

[17] Lv, D., Xu, M., Liu, X., Zhan, Z., Li, Z., & Yao, H. (2010). Effect of biomass species and heating value on product gas composition in biomass steam gasification. Bioresource Technology, 101(12), 4656–4663. https://doi.org/10.1016/j.biortech.2010.01.053

[18] Gil, M. V., Oulego, P., Casal, M. D., Pevida, C., Pis, J. J., & Rubiera, F. (2015). Biomass gasification with air in an atmospheric bubbling fluidized bed: Effect of six operational variables on the quality of the producer gas. Industrial & Engineering Chemistry Research, 54(21), 5520–5529. https://doi.org/10.1021/acs.iecr.5b00045