



Process Simulation and Optimization of Green Hydrogen Production from Rubberwood Sawdust Pellets Via Gasification Using Unisim Design for Oil Refining

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Received: 13 March 2026; Revised: in revised form 02 July 2026; Accepted: 14 August 2026
Available: online 30 September 2026.

ABSTRACT - Indonesia pushes to expand renewable energy to create growing interest in low carbon hydrogen. Rubberwood processing generates large volumes of sawdust that are commonly pelletized for fuel, offering a locally available biomass feedstock for hydrogen rich gas production. This study evaluates the potential of producing green hydrogen from rubberwood sawdust pellets through gasification using process simulation. Feedstock properties were determined through proximate and ultimate analyses and implemented in a two stage simulation framework consisting of pyrolysis followed by gasification. The model was validated against published experimental data for steam gasification of wood residue, and the deviation between predicted and reference gas compositions was evaluated using the root mean square error. After validation, sensitivity analyses were conducted at a gasifier temperature of 700 °C for three gasifying agent configurations: steam only, steam with air, and steam with oxygen. Under steam-only operation, increasing S/B from 0 to 1.0 increased H₂ from approximately 44 to 56 mol%, while HEE increased from about 27 to 36% and LHV decreased from about 11.4 to 8.6 MJ/Nm³. Under steam plus air, increasing S+E/R to about 1.0 reduced H₂ from approximately 56 mol% to near zero while CO₂ increased from about 30 to 85 mol%. Under steam plus oxygen, increasing O/B to 1.0 reduced H₂ from approximately 56 to 22 mol% and increased CO₂ from about 30 to 73 mol%. Overall, the results indicate that steam rich and oxygen lean operation is the most favorable pathway for enhancing hydrogen rich gas production from rubberwood sawdust pellets and provide a simulation basis for selecting operating conditions to support national energy resilience.

Keywords: hydrogen efficiency; lower heating value; cold gas efficiency; refining; sensitivity analysis.

How to cite this article:

Basuki Rahmad Saleh, Irdam Ahmad, Herlina Juni Risma Saragih, Agus Adriyanto, Abdul Rozak Kodarif, Fauzi Yusupandi, Damayanti Damayanti, Muhammad Rifqi, Hanif Fawaz Za'im, and Yazid Bindar, 2026, Process Simulation and Optimization of Green Hydrogen Production From Rubberwood Sawdust Pellets Via Gasification Using Unisim Design for Oil Refining, *Scientific Contributions Oil and Gas*, 49 (3) pp. 667-681.

1. Introduction

Indonesia's abundant renewable energy resources are widely regarded as a strategic advantage that could strengthen its position among global leaders in renewable energy development. In line with this potential, the Indonesian government has established ambitious targets through the national energy policy, aiming to achieve an optimal energy mix of 23% renewable energy by 2025 and further increase it to 31% by 2050 (KESDM 2023). These targets require an accelerated transition away from fossil fuels, which remain a major source of CO₂ emissions, toward cleaner and more sustainable energy systems. In this context, hydrogen (H₂) is increasingly recognized as a promising renewable energy carrier due to its high energy content and its potential to support deep decarbonization.

Currently, hydrogen is utilized in Indonesia within the industrial sector, particularly as a feedstock for fertilizer production. Hydrogen consumption in Indonesia presently stands at approximately 1.75 million tonnes per annum (IEA 2022), with utilization predominantly comprising urea production (88%), ammonia synthesis (4%), and petroleum refining (2%). The remaining utilization was for methanol and metal production. Refining is also a major global hydrogen-demand sector, where hydrogen is used in hydro processing to remove impurities and upgrade heavy petroleum fractions.

Most hydrogen is still produced from fossil fuels, whereas renewable hydrogen remains a small share of total production (Bartoli et al., 2025; Parthasarathy & Narayanan 2014). A Biomass is attractive because it can be converted directly through thermochemical processes, while residues that would otherwise be discarded or burned can be valorized to produce hydrogen-rich gas (Lanjekar et al., 2023; Shen 2024). Biomass is broadly defined as organic material derived from plant or animal sources, which includes tree wood, pruning by-products, and waste materials generated from forestry activities. The rubber tree (*Hevea brasiliensis*) is one of the important forestry commodities in Indonesia, where Indonesia is the second largest rubber producer in the world with a land area of 3.16 million hectares and widespread growth in Lampung Province with an area of 142,600 hectares (BPS 2024). Ministry of Agriculture of The Republic Indonesia has projected the growth of rubber production from 2026 to 2028 using neural network model as shown in Figure 2. Rubber tree wood is usually harvested when it no longer produces rubber sap. The processing of natural rubberwood in the furniture industry results in cutting and processing waste (sawdust/shavings) with percentages of 26.4% and 20.75%, respectively (Jawjit et al., 2024). When the production of rubber increases in the future, the large amount of waster in rubberwood processing was generated.

Several studies showed the rubberwood pellets provide multiple benefits, including more consistent and efficient heat output per unit volume, reduced particulate matter emissions during combustion, and lower shipping costs thanks to their higher bulk density (Ali et al., 2021; Laosena et al., 2022; Saosee et al., 2020). Additionally, barkwood (BW) and sawdust (SD) of rubberwood has been utilized as a fuel through torrefaction process. The findings show that higher torrefaction temperatures and longer processing times substantially enhance the higher heating value of treated biomass to 17–26 MJ/kg, which is similar to the energy content of sub-bituminous coal (Kasawapat et al., 2024). Other works revealed the utilization of rubberwood pellet to produce synthesis gas via gasification (Anis & Zainal 2013; Kaewluan & Pipatmanomai 2011). The recent work by Slatter et al. (2022) exhibited that rubberwood pellet generated higher H₂, carbon monoxide (CO) and LHV compared to eucalyptus wood chip through fixed bed gasifier with CaO as a tar removal catalyst.

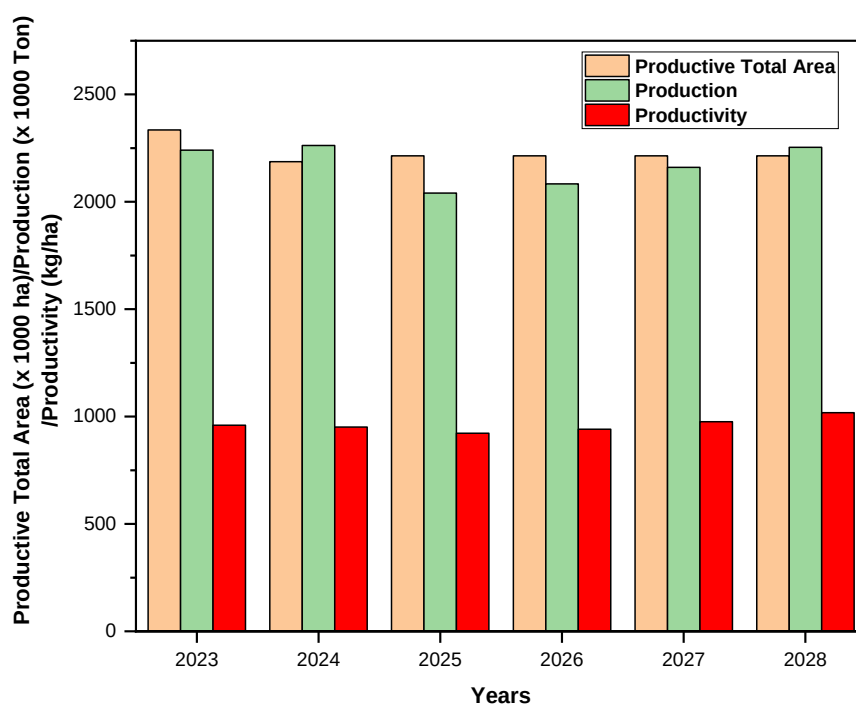


Figure 1.

Outlook of rubber's productive total area, production, and productivity (Chafid, 2025).

Gasification represents a complex thermochemical conversion process involving the simultaneous occurrence of chemical transformations alongside heat and mass transport mechanisms. Process simulation of gasification based on experimental data provides valuable support for optimization (Mutlu & Zeng 2020). Aspen plus was generally used to simulate gasification process with root mean square error (RSME) ranged from 0.35% to 11.84% (Cao et al., 2025; Nemmour et al., 2022; Shi et al., 2025). On the other hand, an alternative software for gasification modelling was unisim design with more simple features and interface. A study by Paiva et al., (2021) showed the gasification process comprised of drying and decomposition modelled by component splitter, then gasification and CO shift tailored by gibbs reactor to accommodate gasification reaction. The composition of gas was close to aspen plus modelling except CO₂ that had large difference about 15%. Moreover, Usmani's et al., (2020) work used a gasifier model consisting of pyrolysis and gasifier unit to conduct thermally integrated gasification. Despite the extensive use of complex simulators like Aspen Plus for biomass gasification modelling, there is a distinct research gap regarding the application of simpler, alternative software such as UniSim Design for evaluating local Indonesian biomass feedstocks. Furthermore, comprehensive comparative analyses evaluating the effects of varying gasifying agents specifically steam, steam-air, and steam-oxygen configurations on the syngas quality derived from rubberwood sawdust pellets remain limited. To bridge this gap, the novelty of this study lies in the development and validation of a simplified, two-stage process simulation framework using UniSim Design to model green hydrogen production from locally sourced rubberwood sawdust pellets in Lampung. By conducting detailed sensitivity analyses on optimal steam and oxidant ratios, this research establishes a novel and practical basis for selecting operating conditions that maximize hydrogen-rich gas production to support national energy resilience.

2. Methodology

Figure 2 exhibited the methodology of this study utilizing UniSim Design R510 for plywood gasification with several performance evaluation. Firstly, the biomass analysis was conducted to obtain proximate and ultimate analysis. For validation, wood residue from Fremaux's work (2015) was put to the UniSim Design R510 for gasification modelling with some parameters. The RMSE was calculated to show the error between experimental data and simulation results. Therefore, the proximate and ultimate from plywood was put to the UniSim Design R510 to observe the variation of the gasifying agent such as steam, steam + O₂, and steam + air. Finally, the several performance evaluations were undertaken based on different gasifying agent in plywood gasification modelling using UniSim Design R510.

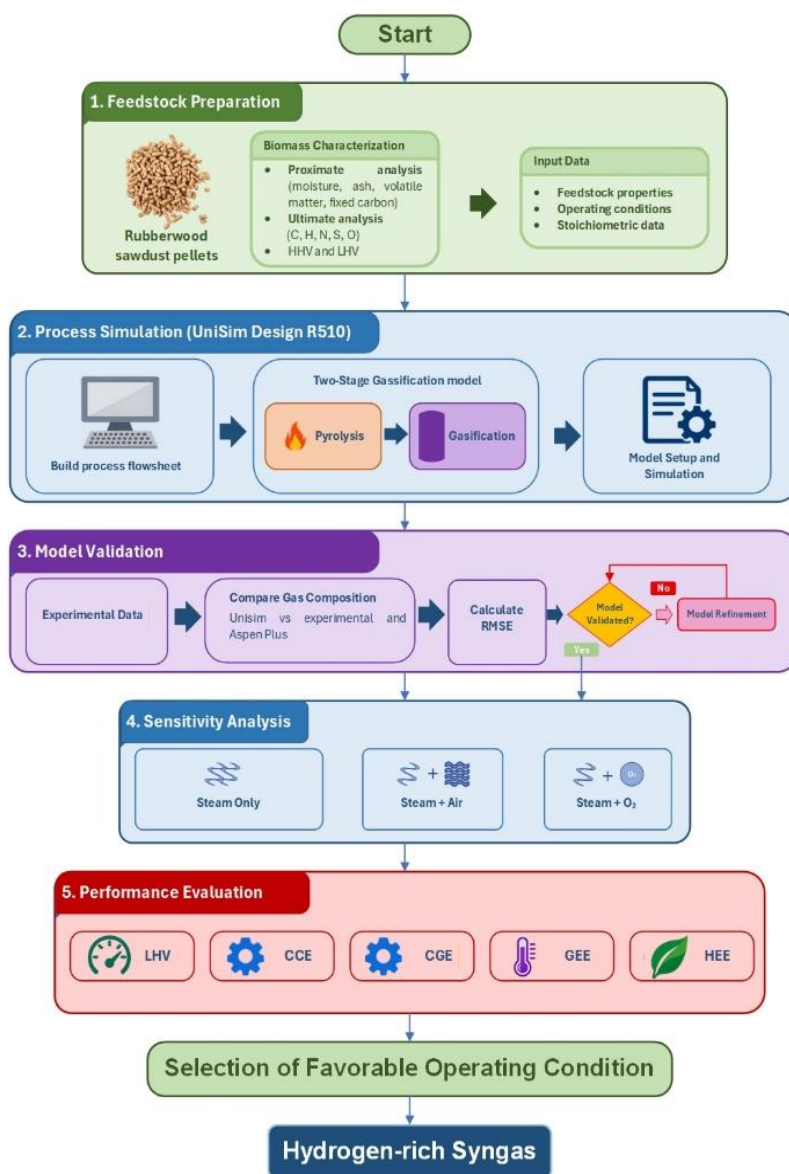


Figure 2.

Schematic workflow of the methodology for hydrogen-rich syngas production.

2.1 Biomass Characterization

The rubberwood sawdust pellet was collected from local company in Lampung, Indonesia. Proximate and ultimate analyses was performed to determine its physicochemical characteristics. Proximate analysis covered total moisture (ISO 18134-1:2015), ash (ISO 18122:2015), and volatile matter (ISO 18123:2015), while fixed carbon was calculated by difference. Moreover, ultimate analysis was performed using a CHN elemental analyzer to determine elemental composition (C, H, N, S, and O) with oxygen content calculated by difference according to the Equation: $O = 100 - (C + H + N + S + \text{ash})$. Moreover, the higher heating value (GCV) and lower heating value (LHV) of sample was determined by ISO 18125:2017 and ISO 1928:2020, respectively.

2.2 Model Validation and Process Simulation

Model development was conducted using UniSim Design R510 from Honeywell, a design suite software that enables the construction of both dynamic and steady-state models under variable environmental conditions. The model validation was referred to study by Fremaux et al., (2015) using wood residue from Aquitaine in France as a biomass feedstock. The proximate and ultimate analysis data of wood residue was shown in Table 1.

Table 1.
Proximate and ultimate analysis of wood residue (Fremaux et al., 2015b)

Ultimate analysis	(wt%)	Proximate analysis	(wt%)
Carbon	50.26	Ash	0.34
Hydrogen	6.72	Volatile Matter (VM)	77.71
Nitrogen	0.16	Fixed Carbon (FC)	16.94
Oxygen	42.66	Moisture Content (MC)	5.01

Steam gasification was carried out by the latter works and the validation was done by steam to biomass ratio (SBR) with range of 0.5 – 1.0 at 700°C. Model accuracy was assessed by quantifying the deviation between experimental observations and predicted values through the root mean square error (RMSE) by following Equation 1 with n denotes the number of data points for model validation. The result from UniSim was compared with Aspen Plus modelling investigated by Vikram et al., (2022) using same biomass feed.

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (Exp_i - Sim_i)^2}{n}} \quad (1)$$

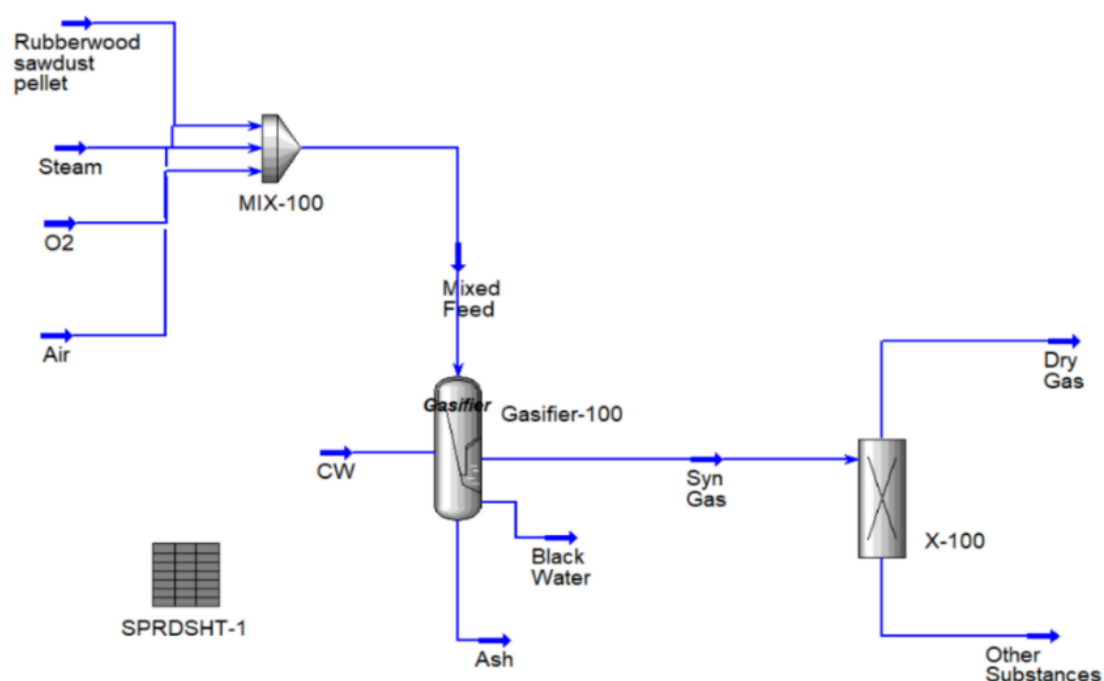


Figure 3.
Process flow for hydrogen production from rubberwood sawdust pellets via gasification.

The thermodynamic package of gasification simulation was Peng-Robinson (PR), similar with other works which used Aspen Plus (Ayorloo et al., 2025; Cao et al., 2025; De et al., 2025; Hantoko et al., 2025). The gasification process of rubberwood sawdust pellets consists of two stages: pyrolysis, and gasification. In pyrolysis process, de-volatilization and volatiles combustion are assumed to be instantaneous and adiabatic while gasification zone was simulated as one-dimensional tubular reactor with the flow field modelled as plug flow, so that axial mixing is negligible. In this process, non-conventional components are converted into conventional components such as carbon, carbon monoxide, hydrogen, carbon dioxide, methane, benzene, H₂S and water. After model validation, the rubberwood sawdust pellets was proceed in gasifier with steam as gasifying agent. The optimal steam conditions produced higher H₂ will be identified using a sensitivity analysis for combined variable with oxygen and air to generate heat. Figure 3 exhibited the gasification model flowsheet for rubberwood sawdust pellet with UniSim Design R510.

2.3 Performance analysis

In the present study, a detailed sensitivity analysis has been carried out on the influence of process parameters such as steam-to-biomass ratio (SBR). The optimal SBR was used for sensitivity of oxygen-to-biomass ratio and equivalence ratio (E/R) or air-to-biomass ratio. The observed parameters consisted of carbon char efficiency (CCE), lower heating value (LHV) of syngas, cold gas efficiency (CGE), gasification energy efficiency (GEE) and hydrogen energy efficiency (HEE) (Ranjan et al., 2024; Sandeep & Dasappa 2013). These parameters were calculated using Eq (2) – (6). An energy requirement for producing oxygen (O₂), known as EO₂, had a value of 305 kWh per ton O₂ with 95% purity while the O₂ purity of 99.5% needed an extra value to 15% (Adnan et al., 2017; Tijmensen et al., 2002). Meanwhile, the E_{steam} was the required energy for steam production calculated by enthalpy equation with 95% assumed efficiency of gas-fired boiler (Bless et al., 2017).

$$HV_{\text{syngas}}(\text{MJ}/\text{Nm}^3) = 10.8 \times y_{\text{H}_2} + 12.6 \times y_{\text{CO}} + 35.8 \times y_{\text{CH}_4} \quad (2)$$

$$\text{CGE} (\%) = \frac{LHV_{\text{syngas}} \times \text{Flowrate}_{\text{syngas}} \times 100}{LHV_{\text{BM}} \times \text{Feedrate}_{\text{BM}}} \quad (3)$$

$$\text{GEE} (\%) = \frac{LHV_{\text{syngas}} \times \text{Flowrate}_{\text{syngas}} \times 100}{LHV_{\text{BM}} \times \text{Feedrate}_{\text{BM}} + E_{\text{steam}} + E_{\text{O}_2}} \quad (4)$$

$$\text{HEE} (\%) = \frac{LHV_{\text{H}_2} \times \text{Flowrate}_{\text{H}_2} \times 100}{LHV_{\text{BM}} \times \text{Feedrate}_{\text{BM}} + E_{\text{steam}} + E_{\text{O}_2}} \quad (5)$$

$$\text{CCE} (\%) = \frac{12 \times GY \times ([\text{CO}] + [\text{CO}_2] + [\text{CH}_4])}{22.4 \times C(\%)} \times 100 \quad (6)$$

3. Result and discussion

3.1 Proximate and ultimate analysis

Proximate and ultimate tests of rubberwood sawdust pellet from local company in Lampung were conducted using international standards and calibrated equipment to guarantee data dependability.

3.2 Model validation with experimental data

Before presenting the effect of steam, oxygen and air ratio in rubberwood sawdust pellet gasification, the developed model should first be validated to ensure its reliability. This validation is carried out by comparing the syngas composition predicted by UniSim Design with reference values reported in the literature, where experimental observations are complemented by simulation results obtained using Aspen Plus (Vikram et al., 2022). The detailed experimental and simulation gas compositions are presented in Figure 4. Across the investigated steam-to-biomass ratios, Aspen Plus consistently shows lower RMS than UniSim, indicating a closer match to the experimental data. The average RMS obtained is 5.8% for Aspen Plus and 11.3% for UniSim, confirming that Aspen Plus produces the best overall agreement for this case. Although UniSim yields higher deviations, its RMS values remain within an acceptable validation range. Specifically, reference studies on gasification model validation reported RMS values in the range of 5.2% to 11.84%, and an RMS of approximately 10% is often considered indicative of high model accuracy (Nemmour et al., 2022). Based on this criteria, the UniSim model showing an average RMS close to 10% can still be regarded as reasonably accurate and suitable for predicting syngas composition trends in the subsequent simulation results.

Table 2.
Proximate and ultimate analysis of rubberwood sawdust pellet

Ultimate analysis	(wt%)	Proximate analysis	(wt%)
Carbon	46.3	Ash	1.6
Hydrogen	6.13	VM	78.2
Nitrogen	0.35	FC	15.4
Oxygen	45.59	MC	4.8
Sulfur	0.03		
HHV (MJ/kg)		18.30	
LHV (MJ/kg)		16.97	

3.3 Effect of steam to biomass ratio

To evaluate the influence of the steam to biomass ratio (S/B) on dry syngas quality, the composition was analyzed at different steam flowrates and at a gasifier temperature of 700°C. The results are presented in the Figure 5. As the steam-to-biomass ratio increases, the dry syngas composition change noticeably CO decreases, while H₂ and CO₂ increase, and CH₄ slightly decreases. This behavior is consistent with the water gas shift reaction (WGS) where additional steam promotes CO conversion into H₂ and CO₂ (Lv et al., 2004). At higher S/B, the changes become more gradual, indicating diminishing gains in H₂ enrichment as the system approaches equilibrium. Consistent with the previous work done with (Hussain et al., 2017) that increasing S/B ratio strongly influences dry syngas composition through WGS reaction especially hydrogen.

As shown in Figure 6, LHV, CCE, CGE, GEE, and HEE was also influenced by S/B ratio where LHV decreases significantly when S/B increasing because the concentration of high-calorific components such as CH₄ and CO is reduced, which are the main contributors to syngas heating value. The CCE increasing a bit from 62.8 to 62.9% due to the increase of gas yield even though the composition of CH₄ and CO decreased. Both CGE and GEE showed a lower value with increasing SBR. CGE is strongly dependent on the heating value of the produced syngas. Since LHV drops sharply with steam addition, CGE follows the same declining pattern. Similar with CGE, GEE depended on LHV syngas and Esteam when SBR raised, the Esteam also increased. In contrast, HEE increases with increasing SBR since water gas shift and steam reforming reaction occurred more often for producing more H₂.

3.4 Effect of steam+air to biomass ratio

To evaluate the influence of the steam + air-to-biomass ratio (S+E/R) on dry syngas quality, the optimal SBR was 1.0 in the sensitivity analysis. Different air flowrates were applied to monitor the syngas composition at 700°C. The resulting dry syngas mole fractions are presented in Figure 7.

As S+E/R increases, the dry gas shifts toward a more oxidative condition CO decreases, while H₂ and CO₂ increase, and CH₄ decreases steadily. This trend indicates that additional air enhances CO conversion via oxidation and increasing CO₂ toward WGS reaction and CO partial oxidation although the presence of steam can promote the WGS under oxygen lean conditions, the observed sharp reduction in H₂ at higher S+E/R suggests that hydrogen is increasingly consumed by oxidation. A consistent with similar observations reported in Aspen Plus simulation work by (Cao et al., 2024).

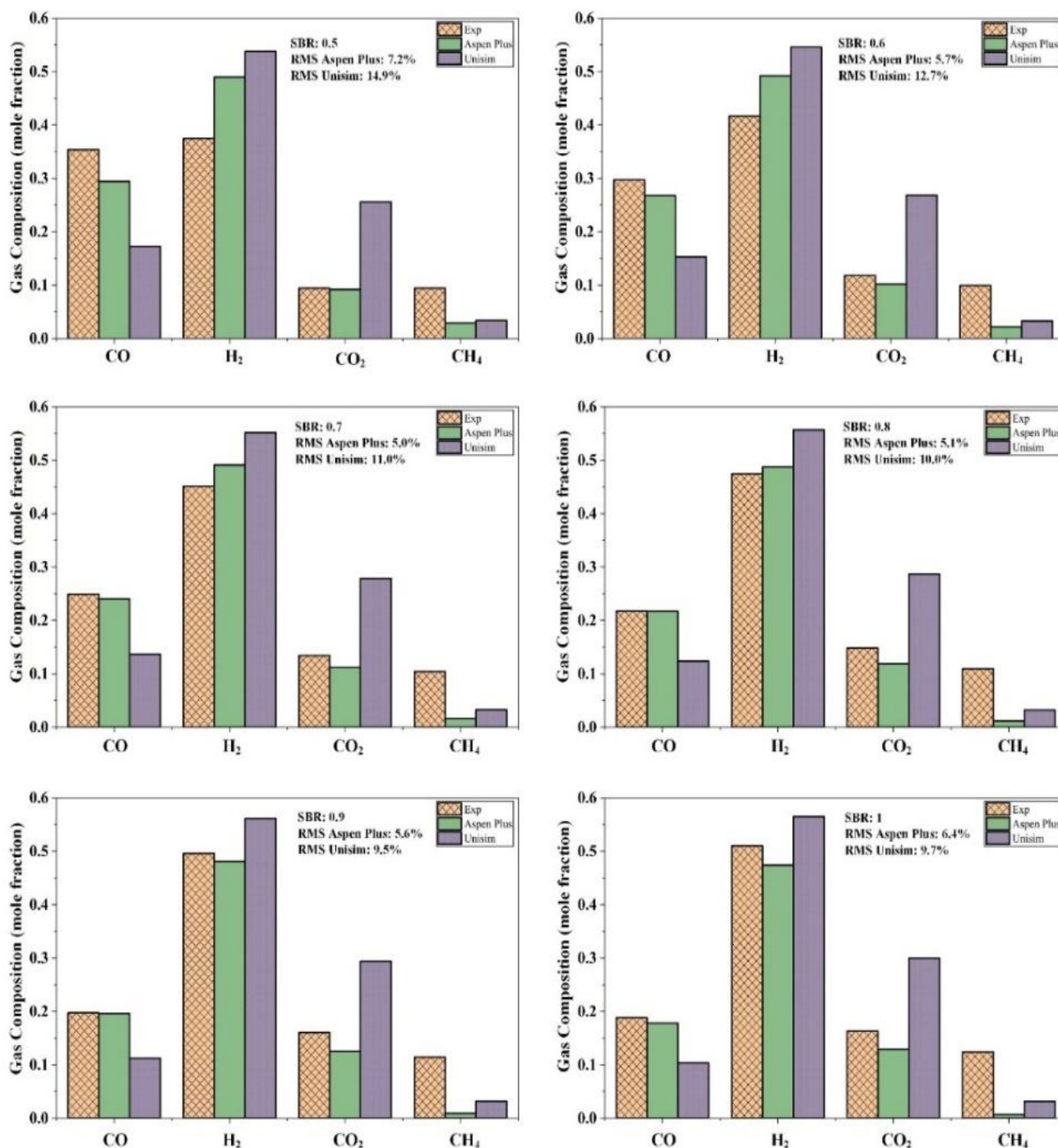


Figure 4.

Validation of UniSim's modelling using hardwood residue with experimental and Aspen Plus at 700 °C

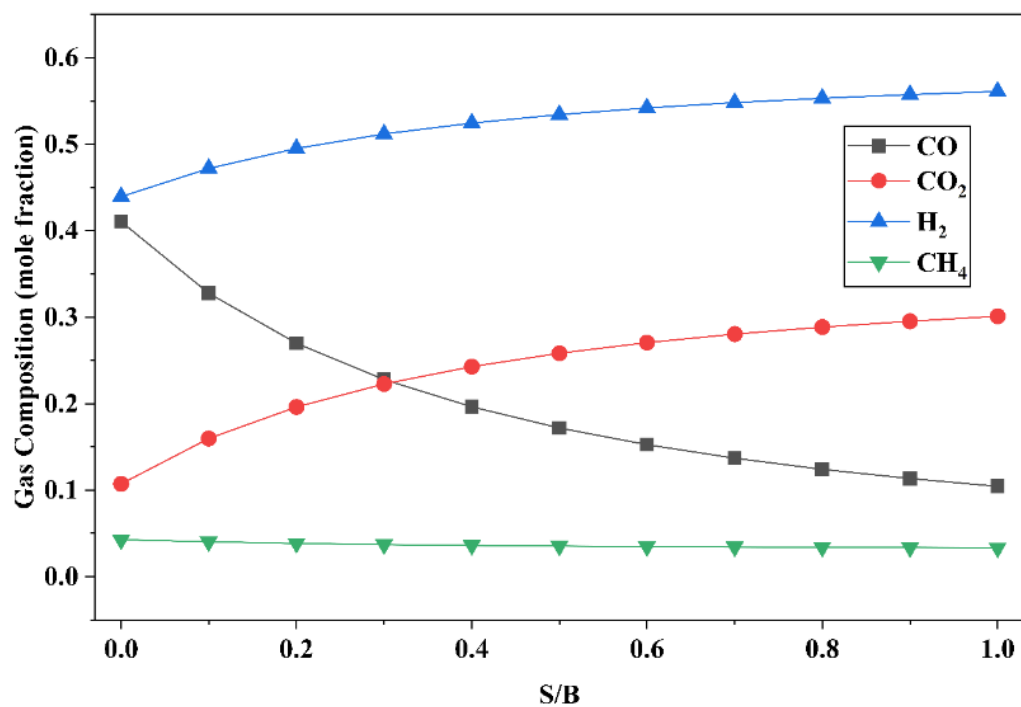


Figure 5.
Dry Syngas Composition at Different S/B Ratios.

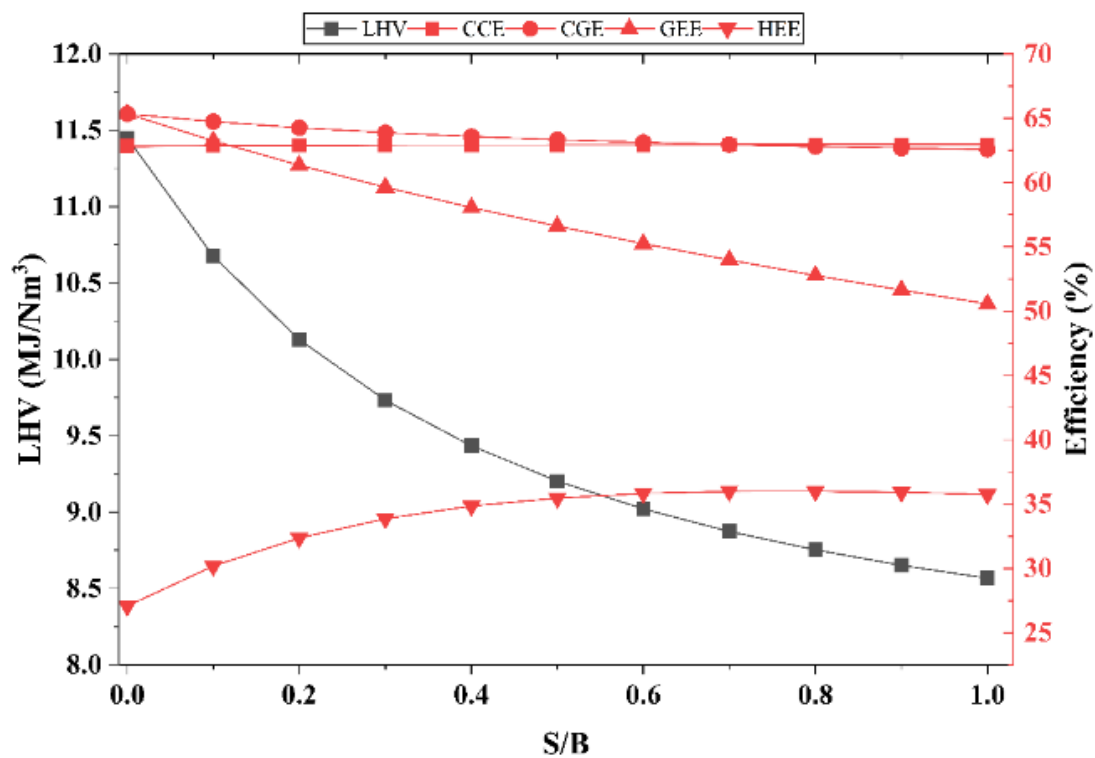


Figure 6.
LHV, CCE, CGE, GEE, and HEE dry syngas at different S/B ratios.

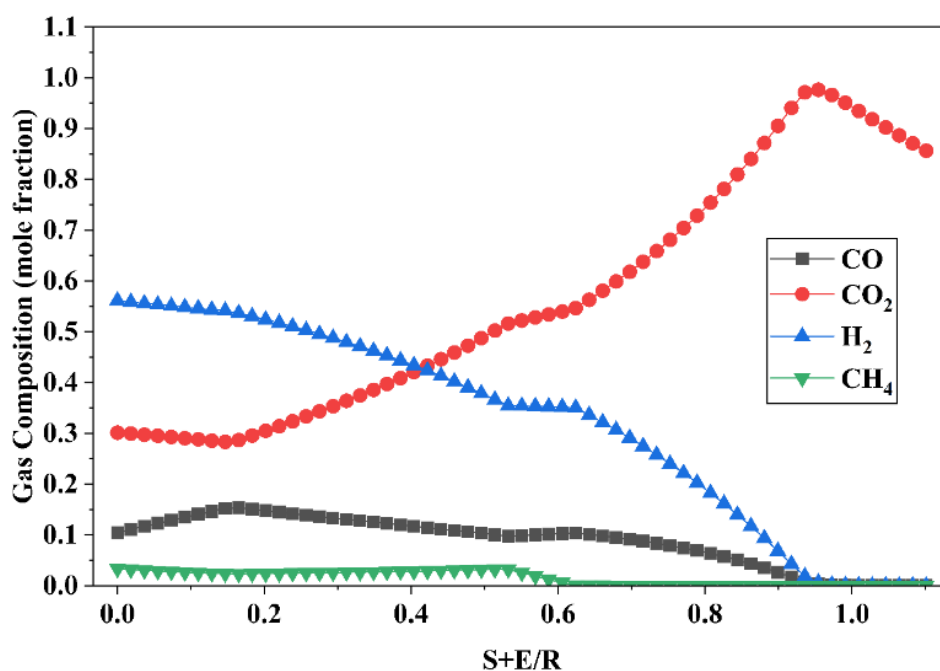


Figure 7.
Dry syngas composition at different S+E/R ratios.

The increasing of E/R reduced significantly of LHV, CGE, GEE and HEE. The LHV decreased due to more oxidation reaction to generate CO_2 , near combustion reaction. The CGE and GEE was influenced by lower LHV with increasing E/R. Meanwhile, the HEE also reduced sharply since H_2 was consumed by O_2 to perform oxidation reaction. On the other hand, the CCE increase from 0.1 to 0.2 then the trend was stagnant. This happened due to the oxidation reaction so that the char was converted to C-containing gas. The result for LHV, CCE, CGE, GEE and HEE was summarized in Figure 8.

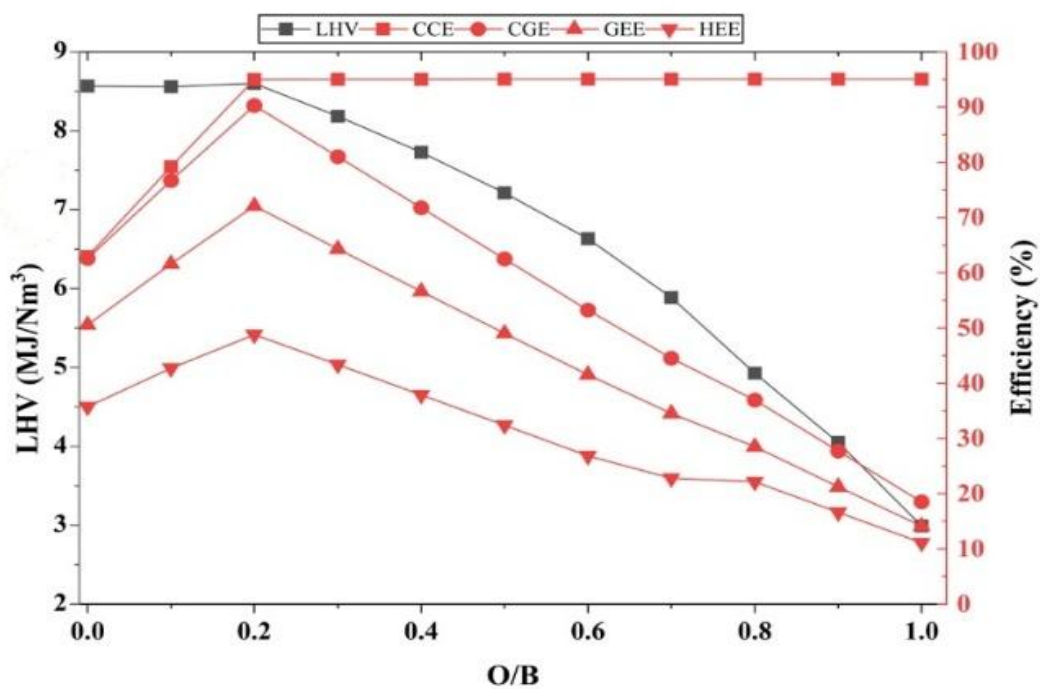


Figure 8.
LHV, CCE, CGE, GEE, and HEE dry syngas at different S+E/R ratios.

3.5 Effect of steam+O₂ to biomass ratio

To evaluate the influence of the steam + oxygen-to-biomass ratio (S+O/B) on dry gas quality, the composition was analyzed at 1000 kg/h steam flowrates and at gasification temperature of 700°C. The resulting dry gas mole fractions are shown in Figure 9.

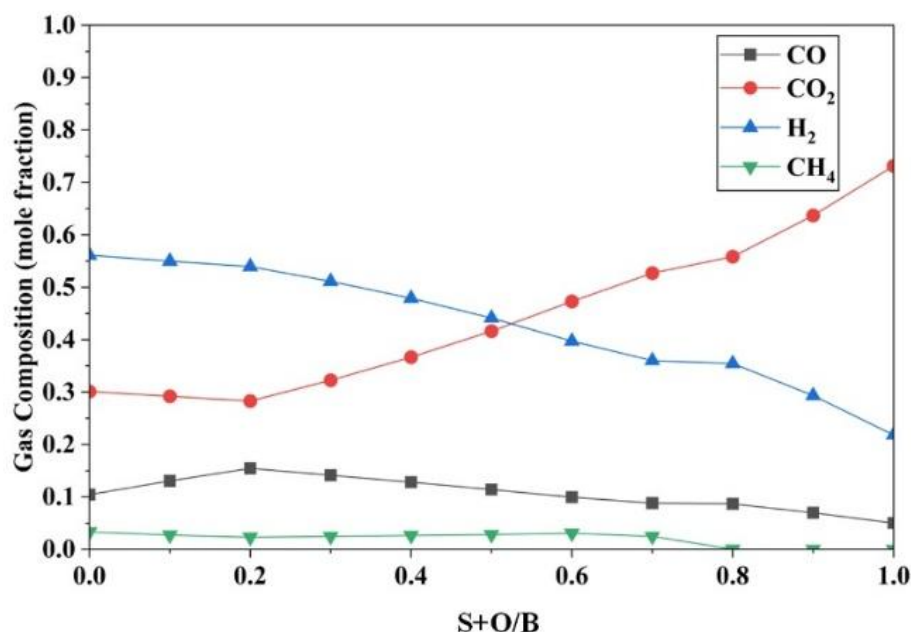


Figure 9.
Dry Syngas Composition at Different S+O/B Ratios.

As S+O/B increases, the dry gas shifts toward a more oxidized. The most important change is the increase of CO₂ accompanied by a decrease of H₂, while CO and CH₄ also decline. This pattern indicates that adding oxygen strengthens oxidation reactions especially conversion of CO to CO₂ and consumption of H₂ to H₂O so the overall syngas quality decreases as combustible components are progressively consumed. Steam-related reactions such as water gas shift may still occur, but under higher oxygen supply their positive contribution to H₂ is outweighed by H₂ oxidation.

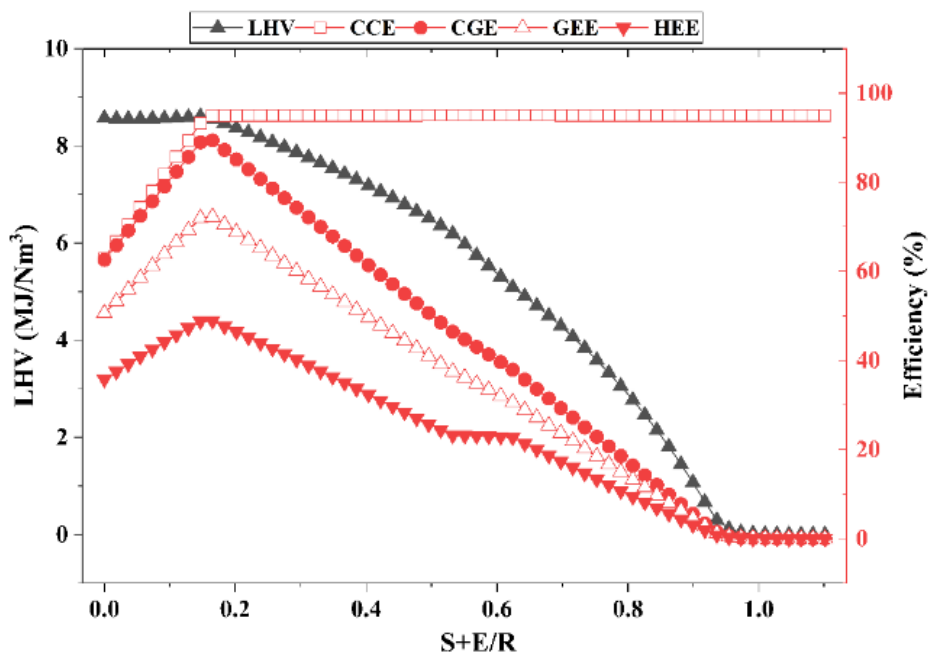


Figure 10.
LHV, CCE, CGE, GEE, and HEE dry syngas at different O/B ratios.

Figure 10 revealed the result of LHV, CCE, CGE, GEE, and HEE dry syngas at different O/B ratios. The trend of O/B ratio was similar with E/R sensitivity. However, this sensitivity required EO_2 as input energy for O_2 production from air separation particularly to calculate GEE and HEE. The presence O_2 or air led to more oxidative reaction and produced more CO_2 that has no LHV.

4. Conclusion

This study demonstrates the feasibility of evaluating hydrogen-rich gas production from rubberwood sawdust pellets using a two-stage UniSim Design process simulation. The model validation gave an average RMSE of 11.3% for UniSim, compared with 5.8% for Aspen Plus, so UniSim was considered suitable for screening process trends despite its larger deviation from the reference data. At 700 °C, steam-only operation increased H_2 from approximately 44 to 56 mol% as S/B increased from 0 to 1.0, while HEE increased from about 27 to 36% and LHV decreased from about 11.4 to 8.6 MJ/Nm³. Under steam-air operation, increasing S+E/R to around 1.0 reduced H_2 from approximately 56 mol% to near zero and increased CO_2 from about 30 to 85 mol%. Under steam-oxygen operation, increasing O/B to 1.0 reduced H_2 from approximately 56 to 22 mol% and increased CO_2 from about 30 to 73 mol%; HEE reached about 48% near O/B = 0.2 before declining. These results indicate that steam-rich and oxygen-lean conditions are more favorable for producing hydrogen-rich gas from rubberwood sawdust pellets. The findings provide a process-level basis for further assessment of biomass-derived hydrogen as a potential contributor to national energy resilience, while experimental validation, energy-economic analysis, life-cycle assessment, gas cleaning, and hydrogen separation remain necessary to establish practical hydrogen yield and system-scale impacts.

5. Acknowledgement

The authors would like to express their sincere gratitude to Indonesia Defense University for supporting this research. We also extend our appreciation to PT. Honeywell Indonesia for providing Unisim Design R510..

6. Declarations

6.1 Author contributions

Basuki Rahmad Saleh: Conceptualization, Writing – Original Draft. Irdan Ahmad: Methodology, Supervision, Writing – Review & Editing. Herlina Juni Risma Saragih: Investigation, Supervision. Agus Adriyanto: Investigation, Supervision. Abdul Rozak Kodarif: Funding Acquisition, Formal Analysis. Fauzi Yusupandi: Software, Validation. Damayanti Damayanti: Formal Analysis, Investigation. Muhammad Rifqi: Data Curation. Hanif Fawaz Za'im: Visualization. Melya Riniarti: Investigation. Yazid Bindar: Supervision, Project Administration, Writing – Review & Editing.

6.2 Funding statement

This work was funded by the Indonesia Universitas Pertahanan.

6.3 Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

6.4 The use of AI or AI-assisted technologies

During the preparation of this work the authors do not use any AI or AI assisted technologies.

7. Glossary of terms and symbols

Terms and symbols	Definition	Unit
BW	Barkwood	-
CCE	Carbon Char Efficiency	%
CGE	Cold Gas Efficiency	%
CHN	Elemental Analysis	-
E/R	Equivalence Ratio	-
EO ₂	Oxygen Equivalence	-
FC	Fixed Carbon	%
GEE	Gasification Energy Efficiency	%
HEE	Hydrogen Efficiency	%
LHV	Low Heating Value	Mj/Nm ³
O/B	Oxygen to Biomass Ratio	-
RMSE	Root Mean Square Error	%
S/B	Steam to Biomass Ratio	-
SBR	Steam to Biomass Ratio	-
S+E/R	Steam Equivalence Ratio	-
S+O/B	Steam, Oxygen to Biomass Ratio	-
WGS	Water gas Shift	-

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