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# Thermodynamic Equilibrium Simulation for Hydrogen-Rich Syngas from Gasification of MSW and Coconut Shells

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**Abstract**: This study addresses the urgent matter of municipal solid waste (MSW) management by exploring its potential conversion into renewable energy through thermochemical processes. Specifically, the research investigates the generation of synthesis gas (syngas) through the gasification process of municipal solid waste, incorporating a biomass blend with coconut shells. Employing a validated thermodynamic equilibrium model, various gasification parameters such as temperature, the composition of biomass, the steam-to-biomass ratio (SBR), the composition of the resulting syngas, the ratio of hydrogen to carbon monoxide ($H_2$/CO), and the ratio of carbon monoxide to carbon dioxide (CO/$CO_2$) were analyzed. The model underwent rigorous validation through comparison with experimental data and simulations from prior research. Simulation outcomes, utilizing steam as the gasifying agent, identified optimal conditions for biomass gasification within the temperature range specified is between 600 and 750°C and an SBR of 0.6 – 1.2. Notably, steam gasification led to an enhancement in the $H_2$/CO ratio, exceeding 3. However, the simulation revealed a lack of compatibility between municipal solid waste and coconut shells, attributed to deviations in the Water Gas Shift Reaction, which skewed leftward. These findings offer significant insights into the complexities and potentials of sustainable waste-to-energy endeavors.

Keywords: Biomass energy; energy conservation; Gasification; Simulation; Syngas

## 1. Introduction

Indonesia has experienced rapid population growth, with an approximate 1.33% increase annually from 2010 to 2018, leading to a surge in municipal solid waste (MSW) production, which reached around 151,921 tons per day (tpd) due to heightened consumption and consumerist lifestyles[1,2]. This escalating waste generation underscores the urgent need for sustainable waste management strategies, particularly as it relates to energy production. Waste-to-energy conversion, notably through gasification, has emerged as a viable solution to address urban waste issues and support renewable energy development[3,4]. Simultaneously, the global community faces challenges associated with the energy crisis and climate change, necessitating a transition towards sustainable and environmentally friendly energy sources. The evolving global energy landscape underscores the importance of exploring alternative energy solutions, such as biomass gasification, to mitigate climate impacts and ensure energy security.

In contrast to combustion, gasification represents a thermochemical process wherein organic matter is transformed into syngas[5–7]. This process shows potential as a renewable energy avenue owing to its capability to yield syngas enriched with carbon monoxide (CO), methane ($CH_4$), hydrogen ($H_2$), and carbon dioxide ($CO_2$). These gases can subsequently undergo further processing to generate electricity, heat, and biofuels. However, the efficiency and environmental impact of gasification process are influenced by factors such as the composition of the feedstock and gasification parameters. Meanwhile, the heterogeneous nature of MSW, characterized by high moisture content and varying organic composition, requires preprocessing before gasification to optimize syngas production[8–11]. High hydrogen content in syngas is desirable for many applications because of its clean combustion properties and high energy content.

The economic viability of waste-to-energy technologies, including gasification, is also a crucial consideration. A decrease in syngas prices, particularly in comparison to non-subsidized retail prices of Liquified Petroleum Gas (LPG), highlights the potential of gasification as a competitive renewable energy solution in Indonesia[12]. However, achieving competitive syngas prices

necessitates understanding the interplay between MSW characteristics, gasification parameters, and syngas quality. Furthermore, Indonesia's abundant coconut production presents an opportunity to utilize coconut shells as a biomass feedstock for gasification, leveraging its high fixed carbon content and energy potential[13,14]. Integrating coconut shells with MSW in the gasification process offers a sustainable approach to waste management while enhancing energy production.

Moreover, gasification parameters, including temperature, equivalent ration, steam-to-biomass ratio, feedstock characteristics, and airflow rates, exert a considerable influence on the composition and quality of syngas[15–20]. However, designing and optimizing gasification systems entail significant costs, underscoring the importance of simulation tools like Aspen Plus for process design and optimization[8–11]. These simulation models, based on thermodynamic equilibrium principles, aid in predicting syngas composition and optimizing gasifier performance [21]. Advanced simulation techniques have also been employed to explore co-gasification of biomass with waste materials and innovative gasification approaches, demonstrating ongoing efforts to enhance syngas production efficiency monoxide [22–25]. Despite advancements, challenges remain in accurately predicting syngas yield and composition, necessitating further research to optimize gasification parameters and improve simulation models[21,24,26]. Therefore, this study aims to address these challenges by employing thermodynamic equilibrium simulation to assess the syngas potential derived from MSW gasification combined with coconut shells.

This research focuses on Serang City, Banten Province, as a case study area due to its relevance to Indonesia's waste management and energy needs. By utilizing process simulation with Aspen Plus V10 software, we aim to analyze the synergistic effects of MSW and coconut shell biomass on syngas production. Our specific objective is to determine optimal gasification parameters that enhance hydrogen-rich syngas production. Recognizing the potential of municipal solid waste (MSW) and coconut shell biomass as viable feedstocks for gasification is imperative for fostering sustainable waste management strategies and advancing the utilization of renewable energy resources. Moreover, optimizing gasification parameters can lead to higher energy yields and cleaner syngas production, thereby contributing to environmental sustainability and energy security.

This research extends upon prior investigations concerning biomass gasification and process simulation, incorporating innovative methodologies to tackle the distinctive complexities presented by municipal solid waste (MSW) and coconut shell biomass. By elucidating the complex interactions between feedstock composition, gasification conditions, and syngas characteristics, we aim to provide valuable insights for policymakers, researchers, and industry stakeholders involved in waste management and renewable energy development. The findings of this investigation hold substantial implications for Indonesia's energy transition, as they can provide valuable insights for the planning and execution of municipal solid waste (MSW) gasification initiatives across the country. By leveraging locally available resources and advanced simulation tools, Indonesia can capitalize on its abundant biomass resources to meet its growing energy demands while reducing environmental impacts associated with waste disposal.

## 2. Methods

### 2.1. Simulation Modeling

This research utilized process simulation methodology through the application of Aspen Plus software. Initially, waste samples were collected from Serang City and analyzed through proximate and ultimate analyses to establish the distinct characteristics of municipal solid waste (MSW), essential for integration into the Aspen Plus software. Similarly, samples of coconut shells (CS) underwent proximate and ultimate analyses to serve as mixed biomass input for the simulation software. The findings from these analyses, presenting the characterization results of both MSW and coconut shells, are synthesized in Table 1.

Table 1. Summary of MSW and CS Characteristics

| Parameters | Unit | Value | |
|---|---|---|---|
| | | MSW | CS |
| *Proximate Analysis* | | | |
| Moisture Content | %, adb | 6.27 | 8.62 |
| Ash | %, adb | 3.98 | 0.48 |
| Volatile Matter | %, adb | 77.33 | 72.78 |
| Fixed Carbon | %, adb | 12.42 | 18.12 |
| *Ultimate Analysis* | | | |
| Carbon | %, adb | 49.07 | 47.63 |
| Hydrogen | %, adb | 6.05 | 6.29 |
| Nitrogen | %, adb | 0.95 | 0.13 |
| Sulfur | %, adb | 0.17 | 0.046 |
| Oxygen | %, adb | 39.79 | 45.42 |
| Gross Caloric Value (GCV) | Cal/g | 4597 | 4464 |

The gasification process was simulated utilizing Aspen Plus software, wherein component IDs or chemical elements were inputted, and a property method was selected to calculate thermodynamic variables. Various streams and blocks were configured within the simulation, representing inputs such as MSW, steam, and outputs such as syngas, as well as reactor and separator units. These components were organized to reflect chemical reaction stages including drying, decomposition, gasification, and combustion. Simulation parameters were defined based on existing literature prior to execution.

The simulation model, constructed from both

experimental and literature-derived data, underwent execution utilizing inputs from Ultimate and Proximate analyses. Syngas composition data, encompassing CO, $CO_2$, $CH_4$, and $H_2$, were evaluated against experimental results for validation purposes, employing the Root Mean Square Error (RMSE/RMS) method, ensuring deviations did not exceed 5.58[27]. Following successful validation, the simulation model integrated Ultimate and Proximate data specific to MSW obtained from laboratory tests. The output data from the MSW gasification simulation comprised essential process parameters, including the influence of temperature on syngas composition, steam-to-biomass ratio (SBR), Higher Heating Value (HHV), and Lower Heating Value (LHV).

Equilibrium modeling within Aspen Plus assessed the MSW gasification process, incorporating a blend of coconut shells with steam. The simulation comprised various component blocks, each designed to represent thermochemical stages in the gasification process. The resulting syngas, consisting of $CH_4$, $H_2$, CO, and $CO_2$, underwent evaluation to determine optimal gasification parameters. For conventional constituents, the Redlich-Kwong-Soave equation with Boston Mathais function (RKS-BM) was utilized, whereas non-conventional components such as biomass and ash employed the HCOALGEN and DCOALGT models. [28]. Figure 1 illustrates a schematic diagram depicting the simulation process.

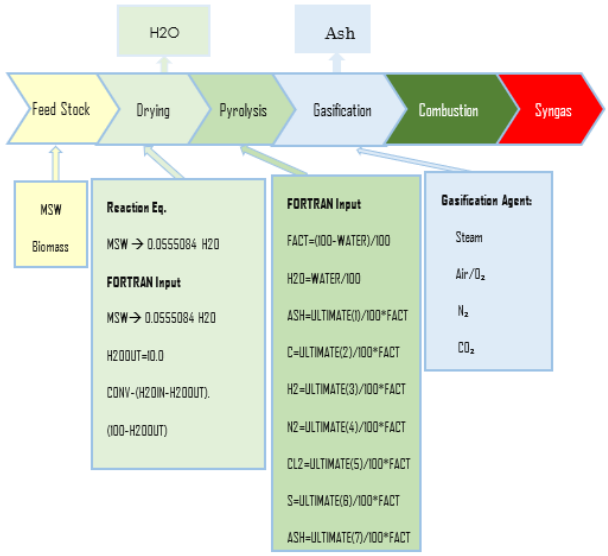



**Fig. 1:** Simulation Modeling Scheme

Biomass, as indicated by ultimate and proximate analysis findings, underwent reactions within the drying block, aiming to remove moisture content from the biomass input (Equation 1). The defined biomass compositions encompassed various ratios, including 100% MSW, 80% MSW: 20% CS, 60% MSW: 40% CS, 40% MSW: 60% CS, 20% MSW: 80% CS, and 100% CS.

$$\text{Biomass} \leftrightarrow \alpha H_2O + \text{Biomass}_{dry} \qquad (1)$$

The simulation made several assumptions, including the maintenance of steady-state and isothermal conditions, the presence of syngas components including $H_2$, CO, $CO_2$, and $CH_4$, the exclusion of tar formation and pressure drop effects, the assumption of thermodynamic equilibrium during chemical reactions, and the application of the Ideal Gas Law.

### 2.2. Validation of Simulation Modeling

To verify the precision of the Aspen Plus simulation model, a comparison was made between the syngas results generated by the simulation and experimental data obtained from literature-supported gasification processes. The experimental investigation conducted by Fremaux et al. (2015), utilizing wood residue from France as the feedstock, constituted the fundamental dataset for the gasification processes[29]. The characteristics of the wood residue feedstock for gasification, as detailed in the literature, are summarized in Table 2. This dataset was also utilized by Vikram et al. (2022) in their research to validate their own modeling approach[27]. In accordance with the parameters specified in the cited research, the gasification of MSW was performed at a temperature of 700°C, while adjusting the steam-to-biomass ratio (SBR) within the range of 0.5 to 1.

Table 2. Wood Residue Characteristics for Validation [29]

| Parameters | Unit | Value |
|---|---|---|
| *Proximate Analysis* | | |
| Moisture Content | %, adb | 5.01 |
| Ash | %, adb | 0.34 |
| Volatile Matter | %, adb | 77.71 |
| Fixed Carbon | %, adb | 16.94 |
| *Ultimate Analysis* | | |
| Carbon | %, adb | 50.26 |
| Hydrogen | %, adb | 6.72 |
| Nitrogen | %, adb | 0.16 |
| Sulfur | %, adb | 0.2 |
| Oxygen | %, adb | 42.66 |

The syngas compositions, expressed as mole fraction percentages of CO, $H_2$, $CH_4$, and $CO_2$, obtained from the Aspen Plus gasification simulation, were subsequently contrasted with the analogous findings reported in the literature. Subsequently, an evaluation was conducted using the root mean square (RMS) calculation to ensure the consistency between the simulated and experimental outcomes. It was ensured that the calculated RMS value did not exceed 5.58 + 1, with the value of 5.58 derived from Vikram et al.'s research [27], serving as the RMS benchmark for model validation [17]. The RMS equation is defined as follows:

$$RMS = \sqrt{\frac{\sum(literatur_{ei} - model_i)^2}{N}} \qquad (2)$$

where $N$ denotes the total number of data points.

## 3. Results and Discussion

### 3.1. Flowsheet of the Gasification Process Simulation

The gasification simulation was set up within the Aspen Plus software, utilizing various components including Material Stream, Heat Stream, Separator Block, Reactor Block, and Calculator. The configuration of these components was informed by the research conducted by Tavares et al. (2020), which provided a fundamental framework for structuring the simulation[28]. The configuration of these blocks is illustrated in the Aspen Plus flowsheet diagram depicted in Fig. 2.

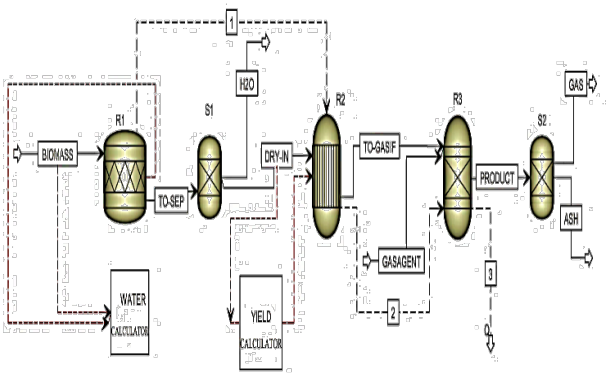



**Fig. 2:** Flowsheet for Biomass Gasification Simulation

Table 3. Description of Blocks in the Model

| Model | Block name | Description |
|---|---|---|
| **RStoic** | R1 | Utilized for modeling conversion reactions with predefined stoichiometry, the emphasis was specifically placed on reducing the moisture content in biomass. |
| **RYield** | R2 | The process entailed simulating reactions with predetermined product composition (yield). This approach demonstrated efficacy in situations where both stoichiometry and kinetics were unknown, yet pertinent data regarding reaction distribution and correlations were available. |
| **RGibbs** | R3 | The modeling of multiphase equilibrium reactions was conducted by minimizing Gibbs Free Energy. This particular block demonstrated significant advantages in scenarios where temperature and pressure were defined, but stoichiometry remained uncertain. |
| **Separator** | S1 | The process of modeling biomass separation using water ($H_2O$) was undertaken. |
| | S2 | The modeling of gas product component separation using ash was conducted. |

The arrangement of blocks within the simulation corresponds to the sequential stages of gasification, including drying, pyrolysis, gasification, and combustion. Material flows are represented by solid black arrow lines, indicating various chemical components, while dashed black lines depict heat or work streams. The functionality of the calculator is outlined by dashed red lines, indicating the input source and output destination. Each block in the flowsheet diagram is described in Table 3.

During the simulation process, specifications for operating conditions, state variables, and composition were inputted for each biomass, specifically municipal solid waste (MSW) and coconut shells (CS). Characteristic data, as detailed in Table 3 within the subtab component attribute, were incorporated. Attributes such as ULTANAL, PROXANAL, and SULFANAL were defined. Within the SULFANAL characteristics, the sulfate value was aligned with the 'S' value in ULTANAL. The total ULTANAL value for ASH was proportionally linked to the ASH value in PROXANAL. It was crucial to ensure that the sum of the total PROXANAL values for Fixed Carbon (FC), Volatile Matter (VM), and Ash (ASH) equated to 100. Additionally, the sum of all ULTANAL component values, excluding ASH, was maintained at 100. This meticulous input of characteristic data was essential to prevent discrepancies, as any deviation could prompt Aspen Plus to issue a yellow warning sign.

### 3.2. Model Validation

In this study, the validation of the Aspen Plus simulation model was carried out through a comparison of experimental data with simulation results obtained from prior research. The experimental data provided by Fremaux et al. (2015) [29] involved the gasification of wood residue at approximately 700°C under SBR conditions ranging from 0.5 to 1. From Table 4, an average Root Mean Square (RMS) value of 5.86 was derived, indicating the degree of concordance between the simulated and experimental data in this study.

The Aspen simulation model developed in this study is validated by comparing it with the research conducted by Pala et al. (2017) [30]. Their study simulated biomass gasification in Aspen Plus at a constant temperature of 900°C and a SBR of 0.2. Table 5 presents a comparison between the simulation data obtained from the literature and the simulation results of this research. By examining both Table 4 and Table 5, the calculation of the RMS value becomes apparent using Equation 2. The average RMS value for comparing the simulation based on Fremaux's experiments with the simulation model in this study is

computed as 5.14. Consequently, the overall average RMS value from experiments and simulations is determined to be 5.5.

Table 4. Validating the model against experimental data for variations in the steam-to-biomass ratio (SBR) in comparison to Fremaux et al. (2015)[29]

| Data | Gas Mole Fraction (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | CO | | $H_2$ | | $CH_4$ | | $CO_2$ | |
| **SBR** | **E*** | **M**** | **E*** | **M**** | **E*** | **M**** | **E*** | **M**** |
| **0.5** | 35.4 | 32.01 | 37.47 | 47.73 | 9.42 | 3.42 | 9.42 | 8.75 |
| **0.6** | 29.71 | 32.16 | 41.65 | 47.54 | 9.93 | 3.40 | 11.77 | 8.83 |
| **0.7** | 24.91 | 32.27 | 45.15 | 47.38 | 10.43 | 3.37 | 13.42 | 8.90 |
| **0.8** | 21.74 | 29.83 | 47.49 | 47.92 | 10.94 | 2.67 | 14.85 | 9.83 |
| **0.9** | 19.72 | 26.82 | 49.61 | 48.22 | 11.45 | 1.97 | 16.05 | 10.91 |
| **1.0** | 18.85 | 24.21 | 51.03 | 48.13 | 12.41 | 1.48 | 16.32 | 11.78 |
| ***Root Mean Square* (RMS)** | | | | | | | | |
| **RMS Value** | 6.00 | | 5.09 | | 8.23 | | 4.12 | |
| **E* = Fremaux Experimental Data**<br>**M** = Aspen Simulation Results Data** | | | | | | | | |

This value is considered acceptable, confirming the validation of the data results from the gasification simulation model developed in this study. Furthermore, this validation is reinforced by the findings of Vikram et al. (2022), who achieved an average total RMS value of 5.58 to validate their model[27].

Table 5. Model Validation with Simulation Data[30]

| Biomass | Gas Mole Fraction (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | CO | | $H_2$ | | $CH_4$ | | $CO_2$ | |
| | **E*** | **M**** | **E*** | **M**** | **E*** | **M**** | **E*** | **M**** |
| **Green Waste** | 21.18 | 21.32 | 60.63 | 43.44 | 0.002 | 0.005 | 17.79 | 9.8 |
| **Food Waste** | 30.22 | 35.51 | 64.39 | 59.68 | 0.04 | 0.225 | 3.99 | 1.1 |
| **MSW** | 18.26 | 15.18 | 65.87 | 43.87 | 0.002 | 0.003 | 15.31 | 8.7 |
| **Pine Sawdust** | 39.19 | 43.73 | 57.09 | 53.91 | 0.07 | 0.479 | 3.36 | 0.6 |
| **Wood Chip** | 35.40 | 38.25 | 56.59 | 50.67 | 0.02 | 0.051 | 7.90 | 4.1 |
| **Wood Residue** | 40.76 | 37.26 | 55.71 | 51.71 | 0.08 | 0.052 | 3.31 | 3.9 |
| ***Root Mean Square* (RMS)** | | | | | | | | |
| **RMS Value** | 3.62 | | 11.99 | | 0.18 | | 4.78 | |
| **E* = Pala Experimental Data**<br>**M** = Aspen Simulation Results Data** | | | | | | | | |

### 3.3. The Impact of Temperature on Syngas Yield

In this study, an evaluation was conducted on gasification temperatures ranging between 600°C and 900°C while maintaining a constant biomass mass flow rate of 0.1 kg/h. Various compositions of municipal solid waste (MSW) with coconut shells were examined, including ratios of 1:0, 4:1, 3:2, 2:3, 1:4, and 0:1. It is assumed that there is no input flow initially. The following presentation illustrates the simulation data for the initial variant, wherein the biomass composition consists of 100% MSW.

The simulation results of MSW gasification are illustrated in Fig. 3 for better understanding. In this gasification process, the highest concentration of $H_2$ is observed at 51.9%, occurring at 900°C. Conversely, at the lowest temperature of 600°C, the concentration of $H_2$ produced is 40.2%. In the temperature range of 600 – 750°C, there is a noticeable rise in the concentration of CO and a significant decline in the concentration of $CO_2$. The optimal quality of syngas is identified within the temperature range of 600 – 650°C. Despite having a lower concentration of $H_2$ compared to higher temperatures, the temperature range between 600 and 650°C exhibits an $H_2$/CO ratio exceeding 2, as depicted in Fig. 5 (a).

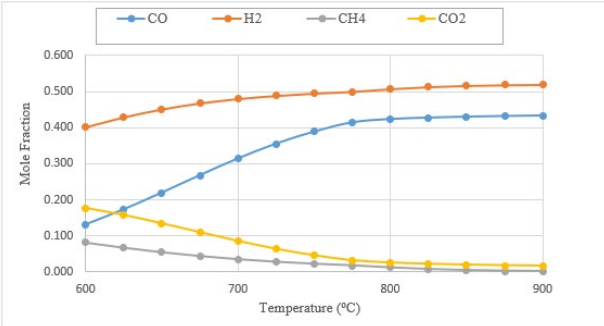



**Fig. 3:** Simulation Results of the Gasification Process with Increasing Temperature, Showcasing the Syngas Composition for MSW Feedstock

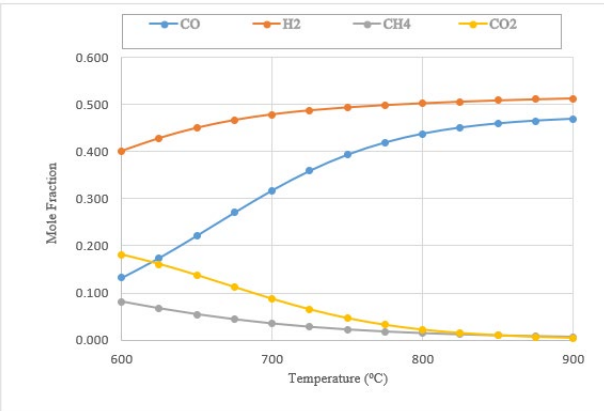
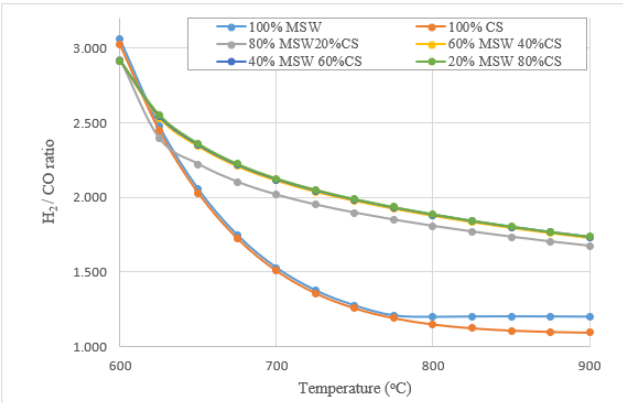



**Fig. 4:** Simulation Outcomes of the Gasification for Coconut Shell (CS) Feedstock, Illustrating the Impact of Increasing Temperature on Syngas Content.

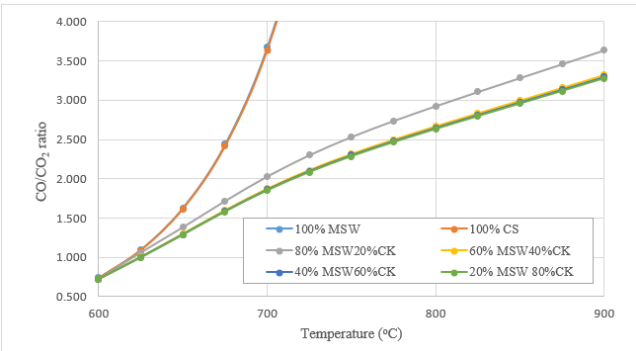
Figure 3 highlights that the optimal concentration of hydrogen ($H_2$) tends to be achieved within the temperature range between 750 and 900°C. Specifically, at 750°C, the $H_2$ concentration reaches 49%, marking a 7% increase compared to the value at 625°C. This significant increase is noteworthy, given that the difference in $H_2$ concentration among temperature variations is typically only around 1%. Therefore, it is advisable to employ temperatures ranging from 700 to 800°C to achieve a high $H_2$ concentration in coconut shell gasification. This

recommendation is rooted in the substantial impact of gasification temperature on producer gas composition. At elevated temperatures, approximately 700 to 800°C, favorable reactions such as the Water-Gas Shift Reaction (WGSR): $CO + H_2O \rightleftharpoons CO_2 + H_2$ and Boudouard Reaction: $2CO \rightleftharpoons CO_2 + C$ occur. These reactions contribute to an increased concentration of $H_2$ in the producer gas[31–34].

The increase in CO concentration demonstrates significance within the temperature range between 600 and 750°C. However, in coconut shell gasification, the concentration of $CO_2$ appears to be higher compared to MSW gasification. Similar to previous biomass variations, within the temperature range between 600 and 650°C, the $H_2$/CO ratio remains above 2, as illustrated in Fig. 5. Despite having a lower concentration of $H_2$ compared to higher temperatures, this ratio indicates good quality in the syngas.




( a )




( b )

**Fig. 5:** Gas Concentration Ratio in Varied MSW to CS Ratio (a) $H_2$/CO Ratio and (b) CO/$CO_2$ Ratio.

In addition to simulating MSW and coconut shell biomass separately, this study also conducted simulations involving mixed biomass. The mass flow rates from each MSW and coconut shell biomass were adjusted according to predetermined variations. Figure 5 illustrates the outcomes of mixed biomass gasification, specifically within a 4:1 ratio of MSW to coconut shell. With a biomass mass flow rate of 0.1 kg/h, the MSW mass flow rate amounts to 0.08 kg/h, while the coconut shell mass flow rate is 0.02 kg/h.

Analysis of Figure 3, Figure 4, and Figure 5 indicates that the concentration of $H_2$ in mixed biomass gasification (4 MSW:1 CS) follows an increasing trend with rising temperature, reaching a peak concentration at 750°C before gradually declining. The maximum concentration of $H_2$, recorded at 750°C, is 48.8%. In contrast to pure biomass (MSW), this co-gasification process demonstrates a relatively higher $CO_2$ yield at higher temperatures, suggesting suboptimal syngas quality production at elevated temperatures. Therefore, it is advisable to operate within the specified temperature range of 700 – 800°C[35,36].

### 3.4. The Impact Steam to Biomass (SBR)

In the gasification process, the introduction of additional compounds aims to enhance syngas quality. When the $H_2$/CO ratio approaches 3, it signifies a syngas with ample hydrogen content, as evidenced in prior studies[37]. Compounds recognized for their ability to improve syngas quality are commonly referred to as gasifying agents, which may include air, steam, or carbon dioxide. In this study, steam at a boiling temperature under 1 atm pressure is utilized. The subsequent discussion elucidates the influence of steam on the $H_2$/CO ratio during MSW gasification at a temperature of 700°C. Figure 6 provides a graphical depiction illustrating the impact of he Steam-to-Biomass (SBR) ratio's effect on syngas quality in MSW gasification at 700°C.

Figure 6a illustrates that increasing the SBR contributes to an enhancement in syngas quality. However, a decline in syngas quality is noticeable within the SBR range of 0.3-0.4, as evidenced by a reduction in the $H_2$/CO ratio from 1.7 to 1.63. Syngas quality tends to improve within the SBR range of 0.5-2. Hydrogen-rich syngas is achieved from an SBR of 1.1 onwards, surpassing an $H_2$/CO ratio of 3. Although the hydrogen concentration tends to decrease with increasing SBR, this is accompanied by a more pronounced decrease in the carbon monoxide concentration. A similar increase in the $H_2$/CO ratio was reported in studies conducted by Bhurse et al., 2024 and Tungalag et al., 2020[37,38]. Figures 6b and 6c depict an enhancement in syngas quality with an increasing SBR using different biomass. To provide a more comprehensive perspective, a three-dimensional graph is presented in Fig. 7, illustrating the influence of temperature and flow rate of steam on the $H_2$/CO ratio.

Observing Figure 7, it becomes apparent that as the gasification temperature increases, the $H_2$/CO ratio decreases, falling below 2. Conversely, increasing the rate of steam flow during the gasification process consistently improves the $H_2$/CO ratio, which is consistent with previous studies[39–41]. This phenomenon can be attributed to the simultaneous impact of the gasification temperature on both the CO and $H_2$ content.

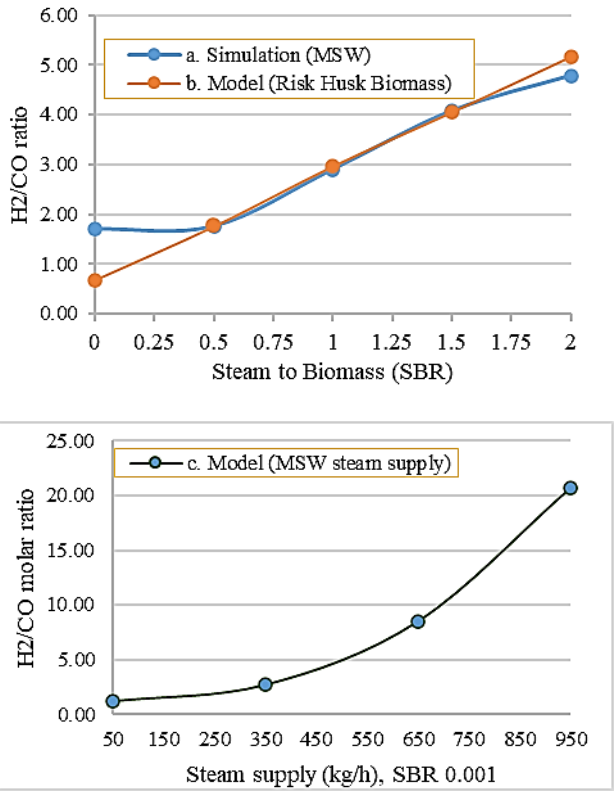



**Fig. 6:** Effect of SBR with different Feed stock (a. Simulation use MSW , b. Model use rice husk biomass[38]), c. Model (MSW steam supply)[37] .

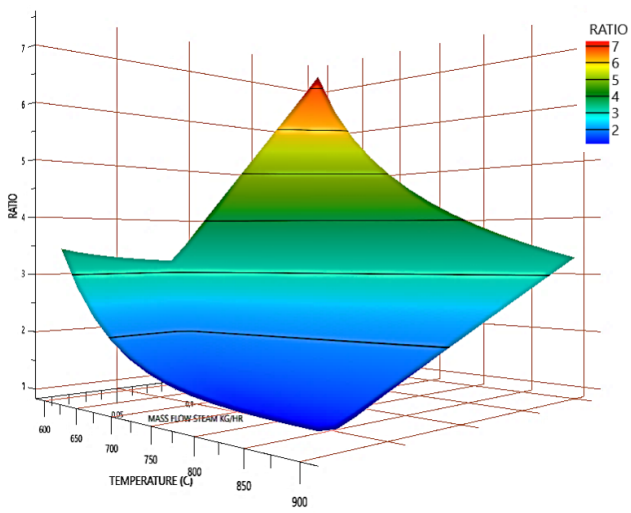



**Fig. 7:** Effect SBR (MSW) in 3D Graph

However, the primary determinant is the concentration of CO, which has the potential to degrade the syngas quality. Optimal conditions for achieving a high-volume fraction of $H_2$ involve operating at a low temperature while maintaining a high Steam-to-Biomass Ratio (SBR)[27]. In this context, a line graph illustrating the correlation between SBR and the $H_2$/CO ratio is not generated, as all variations exhibit a consistent trend: the $H_2$/CO ratio increases with a rise in SBR or steam mass flow rate[42].

### 3.5. Lower Heating Value of Syngas

Based on the discourse regarding biomass gasification and the resultant syngas composition, the lower heating value (LHV) can be determined using the provided equation.

$$LHV = 35{,}81y_{CH_4} + 10{,}79y_{H_2} + 12{,}62y_{CO} \qquad (3)$$

where $y_{CH_4}$, $y_{H_2}$, and $y_{CO}$ are mole fraction of $CH_4$, $H_2$, and CO, respectively.

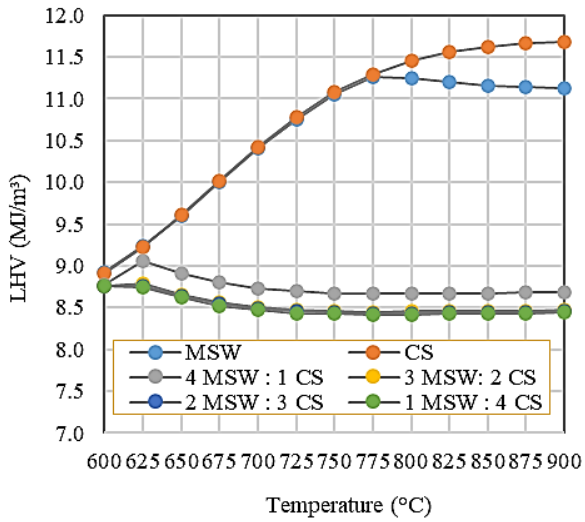



**Fig. 8:** Effect of Temperature to LHV

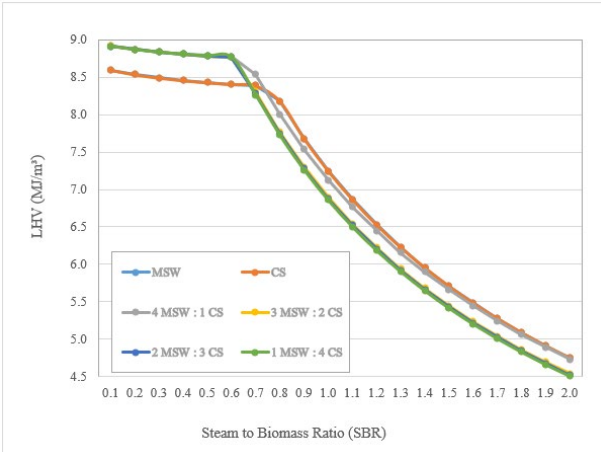



**Fig. 9:** Effect SBR to LHV

The examination of LHV values is conducted under different conditions of the gasification process, taking into account variations in temperature and SBR. This methodology enables a thorough analysis of the affected LHV values. The graphical representation illustrates the influence of temperature on the LHV for each biomass variation during the gasification process.

Across various iterations involving municipal solid

waste (MSW) and coconut shell (CS) biomass, Fig. 8 illustrates a consistent increase in the Lower Heating Value (LHV) with rising temperatures. The maximum LHV value for MSW biomass reaches 11.13 MJ/m³. Conversely, the highest LHV value for coconut shell biomass is achieved at 900°C, registering at 11.68 MJ/m³. The elevation in gasification temperature promotes the generation of gases with heightened $H_2$ and CO content, consequently leading to an augmented LHV[28,41,43]. In contrast, a distinct pattern is observed in the LHV produced by mixed biomass variations, where the decrease is not notably pronounced. Variants such as 3:2, 2:3, and 1:4 exhibit similar graph patterns. A comparable trend is noted in the case of the 4:1 variant, albeit with a slightly elevated graph.

The influence of the SBR on MSW and CS gasification process is illustrated in Fig. 9, indicating a reduction in Lower Heating Value (LHV) as SBR increases. A significant decline in LHV becomes apparent from SBR 0.6 onwards. The inclusion of steam as a gasifying agent leads to a decrease in the concentration of CO within the syngas. Considering the LHV calculation equation, the composition of CO exerts a more pronounced influence on LHV in comparison to the composition of $H_2$. The concentration of CO increases with temperature and decreases with an increasing SBR, emphasizing the greater influence of CO over $H_2$ in LHV calculations[28].

## 4. Conclusion

In conclusion, the gasification simulations utilizing Aspen Plus software across various biomass types have provided valuable insights into optimizing parameters for biomass gasification, with a focus on generating hydrogen-rich syngas. The evaluation of the $H_2$/CO ratio emerges as a reliable indicator, with ratios exceeding 3 indicating favorable hydrogen-rich syngas production. This phenomenon is particularly observable at relatively low temperatures between 600°C and 650°C, coupled with high SBR values ranging from 0.6 to 2. However, the importance of considering the Lower Heating Value (LHV) cannot be overstated, as lower LHV values correlate with inferior syngas quality. The investigation revealed that incorporating coconut shell as a co-biomass with municipal solid waste (MSW) did not significantly impact the gasification process. Notably, simulations suggested a deviation in the Water-Gas Shift Reaction (WGSR), resulting in an increased $H_2O$ fraction in the syngas under certain parameter variations. Consequently, the $H_2$ fraction alone may not serve as a consistent benchmark due to the complex interactions within biomass mixtures. Crucial factors influencing MSW and CS gasification process for hydrogen-rich syngas generation include temperature, SBR, and biomass composition. Based on our comprehensive findings, optimal gasification conditions lie within the temperature range of 600°C to 750°C and an SBR of 0.6 – 1.2. Additionally, a recommended composition of coconut shell with MSW in a ratio of 4:1 is proposed for maximizing syngas quality. These insights contribute to advancing the understanding of biomass gasification processes and provide guidance for optimizing hydrogen-rich syngas production in practical applications.

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