



Comparative Gasification Performance of Cassava Stems, Bagasse, and Sengon Sawdust

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ABSTRACT

Biomass gasification offers a promising route for converting agricultural and forestry residues into syngas fuel, yet comparative studies evaluating multiple feedstocks under matched reactor conditions remain limited. This study presents new experimental gasification data for cassava stems and sugarcane bagasse, obtained using a laboratory-scale fixed-bed reactor, and compares these results against previously reported sengon sawdust data [33] collected under the identical reactor configuration and operating conditions, enabling a directly comparable three-feedstock evaluation. Results show that cassava stems achieved the highest average syngas yield (approximately 75.54%). At the same time, bagasse and sengon sawdust exhibited distinct syngas composition profiles, with bagasse has highest CO — 9.294 vol% and sengon sawdust producing 16.28 vol% of CO. Hydrogen concentration varied across feedstocks and process duration, with bagasse showing the highest H₂ concentration (7.21 vol%) followed by sengon sawdust (5.45 vol%) and cassava stems (5.33 vol%). These findings indicate that feedstock type significantly influences gasification performance and syngas quality, providing a basis for feedstock selection in small-scale gasification applications.

Keywords: biomass gasification, gasification performance, lignocellulosic biomass, syngas production, thermochemical conversion.

1. INTRODUCTION

Driven by the growing global demand for sustainable energy and the urgent need to mitigate greenhouse gas emissions, thermochemical conversion technologies, particularly biomass gasification, have gained increasing attention as promising pathways for renewable energy production [1–3]. Through thermochemical conversion, biomass gasification transforms solid feedstocks into synthesis gas (syngas), primarily CO, H₂, and CH₄, providing a versatile intermediate for electricity generation, fuel production, and chemical

synthesis [4–7]. Compared with direct combustion, gasification offers higher conversion efficiency and greater flexibility for downstream use, making it a promising route to support the transition to low-carbon energy systems [8–10]. Moreover, valorizing agricultural and forestry residues aligns with circular economy principles by transforming biomass waste into value-added energy products while mitigating associated environmental impacts [11–13]. In this context, lignocellulosic residues, including cassava stems, sugarcane bagasse, and wood sawdust, represent abundant yet

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underutilized biomass resources, particularly in tropical regions with substantial availability of agricultural and forestry residues [14,15].

Previous studies on individual biomass feedstocks have demonstrated that variations in physicochemical properties play a critical role in governing syngas yield, gas composition, and tar formation during gasification [16–18]. For example, cassava stems have been reported to possess moderate volatile matter content and favorable reactivity, making them promising feedstocks for thermochemical conversion due to their potential to support efficient devolatilization and gasification reactions [19]. Sugarcane bagasse has received considerable attention as a gasification feedstock owing to its widespread availability, favorable conversion characteristics, and demonstrated suitability for fluidized-bed gasification systems [20]. Meanwhile, sengon (*Albizia chinensis*) sawdust, derived from a fast-growing woody biomass resource, has attracted interest as a gasification feedstock because of its potential to generate favorable syngas quality and its relatively low ash content, both of which may support efficient thermochemical conversion [21]. Comparative investigations of different biomass feedstocks have demonstrated that carbon conversion efficiency, cold gas efficiency, and syngas composition vary significantly as a function of differences in proximate and ultimate properties, which govern feedstock reactivity during gasification [16,22,23]. However, most previous investigations have focused on single feedstocks or restricted binary comparisons under non-uniform operating conditions, thereby limiting rigorous cross-comparison and hindering systematic evaluation of feedstock-dependent gasification performance.

Despite recent progress, a significant research gap persists in the systematic comparative assessment of cassava stems, bagasse, and sengon sawdust under consistent gasification conditions. In many previous studies, key operating parameters,

including equivalence ratio, temperature, and residence time, vary considerably, thereby constraining fair comparison and hindering rigorous evaluation of feedstock-dependent gasification performance [24–26]. Moreover, limited research has investigated the potentially synergistic or contrasting reactivity of these specific biomass feedstocks, particularly within the context of Southeast Asian biomass resources, where comparative thermochemical behavior remains insufficiently understood [27,28]. Another important research gap concerns the insufficient integration of multiple performance indicators, including syngas yield, gas composition, heating value, and process efficiency, into a comprehensive analytical framework for the systematic evaluation of gasification performance [6,29,30]. Furthermore, the effects of intrinsic feedstock properties, particularly ash composition and alkali content, on gasification performance remain poorly understood for these biomass feedstocks, despite their potential to govern reactivity, ash behavior, and process efficiency [30–32]. These gaps highlight the need for a comprehensive, controlled comparative study to generate reliable, generalizable insights.

This study's novelty lies in the direct, systematic comparison of cassava stems, bagasse, and sengon sawdust under consistent gasification conditions, reducing operational variability and enabling a more rigorous assessment of feedstock-dependent thermochemical performance. Unlike many previous studies, this work integrates multiple performance indicators, including syngas composition, gas yield, cold gas efficiency, and carbon conversion efficiency, within a unified experimental framework. In addition, the study explores the relationship between biomass physicochemical properties and gasification behavior, providing mechanistic insight into feedstock reactivity. The focus on regionally abundant biomass resources further strengthens the study's practical relevance, particularly for developing regions with similar feedstock

availability. Collectively, these aspects advance biomass selection strategies for optimized gasification processes.

Based on this framework, this study aims to evaluate the gasification performance of cassava stems, bagasse, and sengan sawdust under controlled operating conditions, with particular emphasis on differences in syngas yields, gas compositions, and process efficiencies among the three feedstocks.

2. RESEARCH METHODS

2.1. Feedstock Preparation

Cassava stems and sugarcane bagasse were collected from Giri Sekar Village and a sugar factory in Yogyakarta, air-dried, and mechanically reduced to a particle size range of 2-4 cm to obtain a relatively uniform particle distribution to minimize variability in heat and mass transfer behavior during conversion, consistent with standard biomass pretreatment protocols [22]. We characterized and prepared sengan sawdust as described in our previous work [33].

2.2. Experimental Setup

We conducted gasification experiments using a laboratory-scale downdraft fixed-bed gasification reactor with an internal diameter of 30 cm and a bed height of 60 cm, operated under controlled conditions. The reactor system included a combustion chamber, biomass feed section, gas outlet line, and syngas sampling port, as shown in Figure 1. K-type thermocouples installed in the reactor zone monitored temperature to observe thermal profiles during gasification. A digital stopwatch was used to record syngas production time, while syngas composition (CO , H_2 , and CH_4) was analyzed using Gas Chromatography–Mass Spectrometry (GC-MS). Additional equipment included an analytical balance for biomass weighing and moisture-conditioning tools for feed preparation.

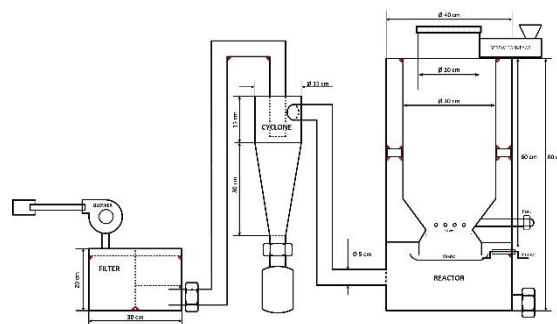


Figure 1. Unit of biomass gasification.

2.3. Experimental Procedure

We newly gasified cassava stems and bagasse for this study under the operating conditions described in Section 2.2. For sengan sawdust, we used the same reactor configuration and operating protocol as in our prior work [33]; we include the resulting dataset here to enable a directly comparable three-feedstock evaluation, and we cite it accordingly in the Results. We introduced the prepared biomass into the fixed-bed gasifier, then ignited and gasified it under identical operating conditions for all treatments. During reactor operation, we continuously monitored temperature changes, recorded syngas production time, and collected gas samples for compositional analysis. We repeated this procedure for all biomass types and loading conditions with five replications per treatment to ensure reproducibility, as shown in Figure 2.

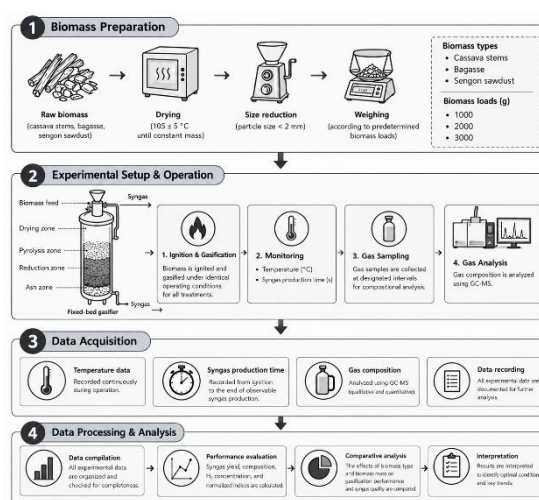


Figure 2. Experimental procedure.

2.4. Syngas Sampling and Analysis

Syngas samples were collected at the end of the gasification unit or after the filter box and analyzed using GC-MS. The instrument was calibrated against certified standard gas mixtures with known concentrations of CO, H₂, and CH₄ before each measurement series.

3. RESULTS AND DISCUSSION

3.1. Comparative Gasification Performance of Cassava Stems, Bagasse, and Sengon Sawdust

Figure 3 demonstrates that biomass type and biomass loading jointly influenced syngas yield and production time during gasification. Cassava stems, gasified in this study, exhibited the most stable syngas yield, ranging from 70.874 to 77.970% with an average of 75.54%, whereas bagasse, also newly gasified in this study, reached the highest peak yield of 80.60% at 1500 g. By comparison, sengon sawdust — gasified under identical reactor and operating conditions in our previous work [33] and included here as a matched-condition baseline — showed the lowest average syngas yield (64.91%). Furthermore, syngas production time increased substantially with increasing biomass loading for all three feedstocks, indicating a positive biomass loading–residence time relationship. Bagasse exhibited the shortest average production time (4524 s) compared with cassava stems (7540 s) and the previously reported sengon sawdust value (9360 s) [33], indicating faster gasification behavior. At higher biomass loads, the pronounced increase in production time observed for cassava stems and sengon sawdust [33] may indicate the onset of transport limitations. Taken together, these results — combining new experimental data for cassava and bagasse with the previously characterized sengon dataset [33] — suggest a trade-off between syngas yield and process duration, with cassava stems showing the most stable overall performance and bagasse offering the most favorable compromise between yield and gasification time.

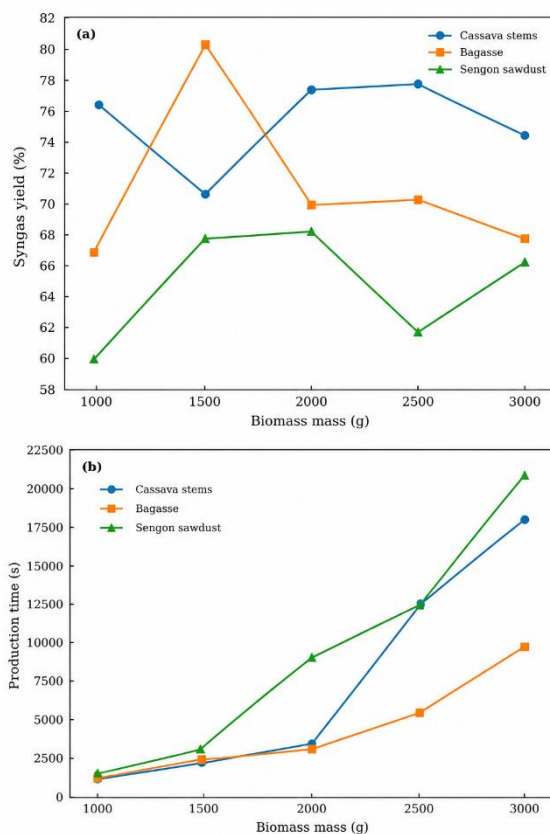


Figure 3. Comparative gasification performance of cassava stems and bagasse (newly obtained in this study) and sengon sawdust (previously reported in [33] gasified under identical conditions) in terms of (a) syngas yield and (b) syngas production time as a function of biomass mass.

The performance behavior observed in Figure 3 suggests that differences in syngas yield and production time are closely linked to intrinsic feedstock characteristics, particularly volatile matter content, ash composition, and fixed carbon fraction, which govern devolatilization pathways and char reactivity during gasification. Consequently, observed performance variations may reflect feedstock-dependent reaction behavior rather than biomass loading alone. This interpretation aligns with Suparmin et al. [16], who showed that biomass physicochemical properties significantly influence syngas productivity and overall conversion efficiency. The stable performance observed for cassava stems may be attributed to balanced feedstock reactivity and favorable thermal conversion

characteristics, consistent with previous studies indicating that moderate volatile matter content can sustain gasification reactions while minimizing excessive tar formation and secondary conversion losses [6].

The favorable combination of high syngas yield and shorter production time observed for bagasse may be attributed to improved heat and mass transfer characteristics, consistent with fluidized-bed studies indicating enhanced conversion kinetics for sugarcane bagasse, potentially associated with its fibrous structure and relatively low diffusion resistance [20]. However, the prolonged production time observed at higher biomass loadings may be attributed to transport limitations and possible bed compaction effects, both of which can restrict reactant diffusion and have been reported to reduce gasification efficiency under elevated feed rates [34–36]. In contrast, the relatively lower efficiency observed for sengan sawdust may be attributed to slower char conversion despite its favorable low-ash properties. Although this finding partially contrasts with studies reporting improved syngas quality for woody biomass, the discrepancy may arise from differences in reactor configuration, particle packing behavior, and associated transport limitations that can suppress effective conversion [21]. Theoretically, these findings reinforce the idea that feedstock selection in gasification cannot rely solely on calorific or compositional criteria but must also consider kinetic-process interactions. In practice, the results suggest that bagasse and cassava stems are better suited to optimizing syngas productivity under moderate loading. In contrast, sengan may require pretreatment or reactor modifications, providing useful guidance for feedstock-specific gasifier design and tropical biomass valorization strategies.

3.2. Effect of Biomass Mass on Syngas Quality

Figure 4 demonstrates that biomass type significantly influenced syngas quality, as

reflected in both CO concentration and the CO/H₂ ratio. Sengan sawdust — gasified under identical reactor and operating conditions in our previous work [33] — consistently produced the highest CO concentration, ranging from 15.402 to 17.235 vol% with an average of 16.28 vol%, markedly higher than the newly measured values for cassava stems (7.57 vol%) and bagasse (7.42 vol%), both gasified in this study. By comparison, bagasse reached a peak CO concentration of 9.294 vol% at 2000 g, suggesting a possible optimum gasification condition, whereas cassava stems showed relatively stable CO generation across the biomass loading range. The CO/H₂ ratio further revealed contrasting syngas characteristics among the feedstocks. Sengan sawdust exhibited the highest average CO/H₂ ratio (3.42) [33], indicating a CO-rich syngas, whereas bagasse showed the lowest mean ratio (1.11), suggesting a comparatively H₂-enriched syngas; cassava stems displayed intermediate behavior with an average ratio of 1.56. Moreover, the decline in the CO/H₂ ratio for sengan at 2000 g [33] may indicate enhanced hydrogen formation under this condition. Overall, these results—combining new data for cassava and bagasse with the previously reported sengan dataset [33]—confirm that feedstock properties strongly affect syngas composition, with sengan favoring CO-rich gas production and bagasse yielding a more balanced syngas composition.

The syngas quality trends observed in Figure 4 suggest that feedstock-dependent differences in CO concentration and CO/H₂ ratio are closely linked to intrinsic biomass characteristics, particularly lignin content, volatile matter, and mineral constituents, which govern char–gas reactions and secondary cracking pathways during gasification. Moreover, these differences may reflect variations in feedstock-dependent reaction pathways and gas-phase conversion behavior that influence syngas selectivity. This interpretation is consistent with Suparmin et al. [16] who demonstrated that variations in elemental composition and

ash chemistry significantly affect syngas composition and gasification selectivity. The comparatively higher tendency for CO-rich syngas observed for sengon sawdust may be attributed to enhanced carbon conversion through the Boudouard reaction and char gasification pathways. This interpretation is consistent with studies suggesting that woody biomass can promote elevated CO generation owing to high fixed-carbon reactivity and relatively low ash interference, both of which may favor carbon conversion toward CO formation [21].

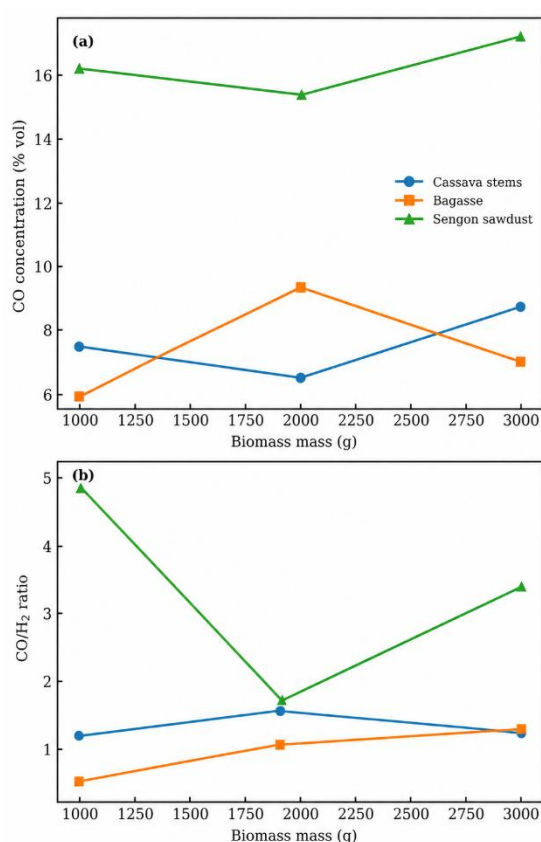


Figure 4. Effect of biomass mass on syngas quality represented by (a) CO concentration and (b) CO/H₂ ratio during gasification of cassava stems and bagasse (newly obtained in this study) and sengon sawdust (previously reported in [33] gasified under identical conditions).

The comparatively lower CO/H₂ ratio observed for bagasse may reflect a shift toward hydrogen-promoting reactions, potentially associated with enhanced volatile release and water–gas shift activity, both of

which may favor increased hydrogen selectivity. This interpretation is consistent with Amaro et al. [20], who demonstrated that sugarcane bagasse can promote syngas upgrading and hydrogen formation under suitable reaction conditions. However, the non-monotonic response of the CO/H₂ ratio to biomass loading may reflect how operating conditions influence competing reforming and shift reactions, suggesting that syngas composition is governed by coupled reaction pathways and feedstock–process interactions rather than feedstock composition alone. This interpretation is consistent with Gao et al. [6], who demonstrated the importance of such coupled interactions in controlling gas composition.

From a theoretical perspective, these findings reinforce the view that syngas quality should be interpreted in terms of integrated reaction chemistry rather than single-gas concentrations alone. In practice, the results suggest that sengon sawdust may be advantageous for CO-rich syngas applications, such as synthesis gas production. In contrast, bagasse appears more suitable for hydrogen-oriented gasification systems. This has implications for feedstock-specific gasifier optimization and for designing thermochemical pathways aligned with targeted downstream energy or chemical applications.

3.3. Effect of Biomass Mass on Syngas Methane Characteristics

Figure 5 demonstrates that methane formation during gasification was significantly influenced by feedstock type and biomass loading. The methane generation behavior observed in Figure 5 suggests that CH₄ formation may be governed primarily by feedstock-specific devolatilization pathways, char hydrogenation reactions, and catalytic effects associated with inherent mineral species, rather than by biomass loading alone. Moreover, the observed methane distribution may reflect differences in feedstock-dependent reaction pathways and secondary

gas-phase conversion behavior that influence methanation selectivity.

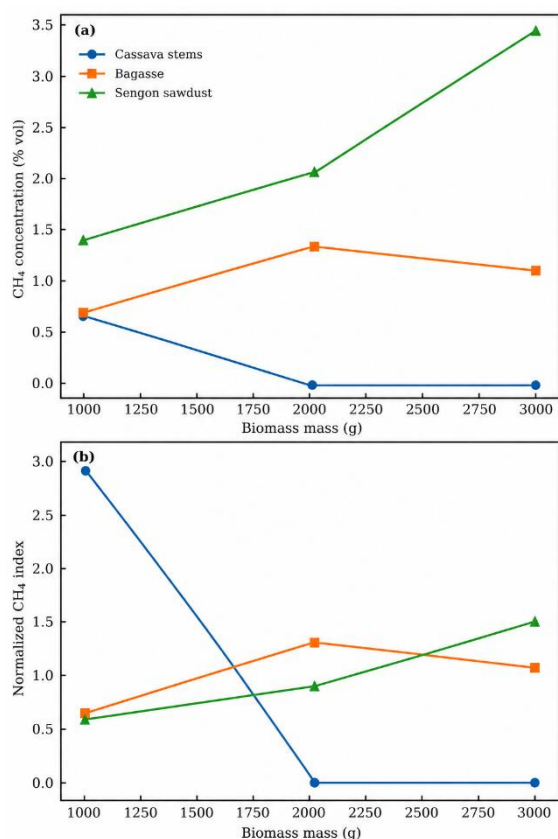


Figure 5. Effect of biomass mass on syngas methane characteristics represented by (a) CH₄ concentration and (b) normalized CH₄ index during gasification of cassava stems and bagasse (newly obtained in this study) and sengon sawdust (previously reported in [33] gasified under identical conditions).

This interpretation aligns with Gao et al. [6], who showed that methane formation is highly sensitive to biomass composition, secondary reforming reactions, and reactor environments. The stronger tendency toward methane enrichment observed in sengon sawdust may be attributed to the lignin-rich character of woody biomass, which can promote hydrocarbon-cracking intermediates and methanation pathways that favor CH₄ production. This interpretation is consistent with Waziri et al. [21], who showed that wood-derived feedstocks may improve hydrocarbon gas quality and reduce mineral interference during thermochemical conversion.

The reduced methane formation observed for cassava stems at higher biomass loading may be attributed to intensified methane reforming or enhanced hydrocarbon oxidation under prolonged residence conditions, both of which may suppress net CH₄ formation. This interpretation is consistent with López-García et al. [13], who demonstrated that methanation and reforming reactions can strongly compete under varying gasification conditions. Meanwhile, the intermediate methane formation behavior observed for bagasse may reflect a transition between volatile-driven methanation and secondary cracking losses, suggesting a balance between methane-forming and reforming pathways. This interpretation aligns with studies showing that sugarcane bagasse can exhibit mixed reforming–methanation behavior depending on operating conditions [20].

Theoretically, these findings reinforce that methane should be considered not merely a minor syngas component but an indicator of competing gasification sub-reactions and feedstock-dependent reaction pathways. In practice, the higher methane potential of sengon suggests suitability for fuel-gas applications requiring a higher calorific value. In contrast, lower methane formation in cassava may favor cleaner syngas routes for synthesis applications. These outcomes provide useful implications for feedstock selection and reactor optimization targeting specific downstream gas utilization.

3.4. Effect of Biomass Mass on Hydrogen Characteristics

Figure 6 shows that hydrogen formation was strongly dependent on both biomass type and biomass loading, with distinct response patterns among feedstocks. Bagasse, newly gasified in this study, produced the highest mean H₂ concentration (7.21 vol%), followed by sengon sawdust (5.45 vol%) — gasified under identical conditions in our previous work [33] — and cassava stems (5.33 vol%), also newly gasified in this study. Bagasse exhibited maximum H₂ production at 1000 g (9.057 vol%), followed by a continuous

decline to 4.795 vol% at 3000 g, whereas sengan reached peak hydrogen concentration at 2000 g (8.002 vol%) [33], suggesting optimal conditions for hydrogen-generating reactions. Cassava stems showed a non-monotonic trend, decreasing to 2000 g and then recovering to 6.327 vol% at 3000 g. The normalized H_2 index in Figure 6(b) further indicates contrasting hydrogen-enrichment behavior, with sengan [33] showing the strongest relative enhancement at intermediate loading, whereas bagasse exhibited progressive suppression at higher mass. These results — combining newly obtained cassava and bagasse data with the previously reported sengan dataset [33] — suggest that hydrogen generation was governed by feedstock-specific reaction pathways, with bagasse favoring higher overall H_2 yield and sengan exhibiting stronger selective enrichment under moderate biomass loading.

The hydrogen production behavior observed in Figure 6 indicates that H_2 formation is governed by complex interactions among feedstock composition, reforming reactions, and gas–solid reaction pathways, rather than by biomass loading alone. This interpretation agrees with Gao et al. [20] who emphasized that hydrogen generation in biomass gasification depends heavily on volatile release, char reactivity, and competition among steam reforming, water–gas shift, and methanation reactions. The comparatively high hydrogen production associated with bagasse may reflect favorable volatile-matter conversion and enhanced water–gas shift activity, consistent with studies reporting that sugarcane bagasse can promote H_2 -rich syngas due to its oxygenated structure and reactive char behavior [20].

The hydrogen enrichment peak observed for sengan at intermediate biomass loading suggests that woody biomass may favor secondary reforming pathways under optimal residence conditions, supporting findings by Waziri et al. [20] that low-ash woody feedstocks can improve syngas quality through enhanced reforming efficiency. However, the decline in hydrogen

concentration at higher biomass loading also suggests diffusion limitations or competing methane-forming reactions, consistent with previous research, which reported that increased feed loading may shift gasification equilibria and reduce hydrogen selectivity [36–38].

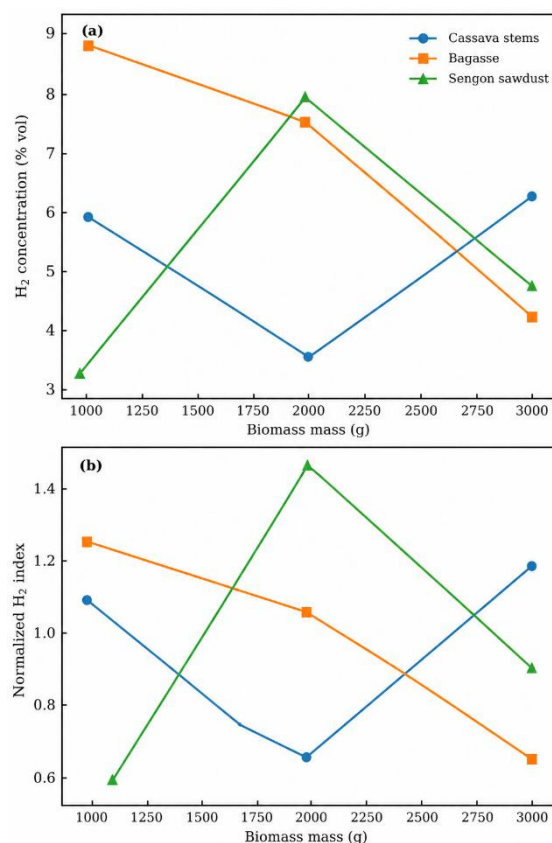


Figure 6. Effect of biomass mass on hydrogen characteristics represented by (a) H_2 concentration and (b) normalized H_2 index during gasification of cassava stems and bagasse (newly obtained in this study) and sengan sawdust (previously reported in [33], gasified under identical conditions).

Theoretically, these findings reinforce the view that hydrogen formation should be interpreted in terms of integrated reaction-network behavior rather than isolated gas-composition analysis. In practice, bagasse appears promising for H_2 -oriented gasification applications, while sengan may be advantageous within optimized operating windows. These results have useful implications for feedstock selection and

reactor optimization for targeted syngas upgrading and hydrogen-rich gas production.

4. CONCLUSION

This study confirms that biomass type critically determines gasification performance, revealing distinct trade-offs among syngas yield, composition, and production time. Drawing on new experimental data for cassava stems and bagasse, combined with previously reported sengan sawdust results obtained under identical reactor and operating conditions [33], cassava stems exhibited the most stable overall syngas yield, indicating suitability for reliable and consistent gasification. Bagasse showed the highest peak syngas yield and hydrogen concentration under specific conditions, although its sensitivity to biomass loading suggests an optimal operating window. In contrast, sengan sawdust produced higher CO and CH₄ concentrations [33], indicating potential for higher-calorific syngas applications, despite longer production times and lower overall syngas yield. These findings reinforce the role of intrinsic biomass properties and transport-related effects in shaping reaction pathways and syngas quality, and support the broader literature on feedstock-dependent gasification behavior. This study is limited in several respects: performance was assessed using syngas yield and composition alone, without cold gas efficiency, carbon conversion efficiency, or heating value determination; proximate and ultimate characterization of the feedstocks was not performed, limiting mechanistic interpretation of the observed trends; and results are confined to a single fixed-bed reactor configuration without kinetic or tar analysis. Future work should address these gaps directly — incorporating feedstock characterization data, calculating cold gas and carbon conversion efficiencies, and applying statistical analysis of replicate measurements — alongside broader investigation of co-gasification strategies, alternative reactor designs, and process

optimization through temperature, equivalence ratio, and catalytic enhancement.

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AUTHOR CONTRIBUTIONS

A.A.: Conceptualization, methodology, investigation, resources, formal analysis, writing – original draft, writing – review & editing, project administration. **M.M.:** Conceptualization, methodology, formal analysis, supervision, review & editing. **M.R.A.:** Investigation, data curation, formal analysis, writing – original draft. **A.M.:** Formal analysis, visualization, review & editing. **N.A.Z.A.:** Investigation, formal analysis, validation, review & editing. **S.Z.A.:** Supervision, review & editing.

CONFLICTS OF INTEREST

The authors declare no competing financial interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used ChatGPT to assist in the linguistic domain for clarity, conciseness, and readability during the initial drafting. Claude was subsequently utilized to assist with language refinements during manuscript revision. All AI-assisted content was critically reviewed, revised, and validated by the human authors, who maintain full responsibility for the integrity and accuracy of the work.

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