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Preliminary Study on the Characterization of Congolese Rice Straw and Determination of Its Syngas and Hydrogen Production Potential

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Abstract: ***This study investigates the potential of Congolese rice straw as a renewable feedstock for hydrogen - rich syngas production through gasification. Proximate and ultimate analyses revealed a high volatile content and favorable elemental composition for energy generation. Gasification was conducted under both air and steam conditions using a fixed - bed downdraft reactor. Results showed hydrogen yields of 24.92% and 45.00% by volume under air and steam gasification, respectively. Steam gasification at 800°C demonstrated superior performance, producing 17.97 mmoles of hydrogen per gram of biomass. These findings underscore the viability of utilizing agricultural residues like rice straw for decentralized energy solutions in regions such as the DRC.***

Keywords: rice straw gasification, hydrogen production, biomass characterization, steam gasification, syngas composition.

1. Introduction

Rising energy needs and finite hydrocarbon resources necessitate renewable alternatives for sustainable development [1]. Biomass from agricultural and forestry waste is a key renewable source, offering an eco - friendly substitute to fossil fuels through energy conversion [2]. Pyrolysis/gasification converts biomass into syngas—a mix of CO, CO2, and H2—used in engines or to make chemicals and fuels. H2, a clean energy source [3], [4], can also be produced, with performance influenced by feedstock type, gasifier design, and operational factors [5], [6]. For instance, a study revealed that an optimal equivalent ratio (ER) of 0.29 - 0.34 enhances gas quality, while uniform rice straw feedstock size and lower moisture content improve gasification performance and syngas heating value [7].

Agricultural residues, particularly rice straw, are abundant and cost - effective energy sources. Despite producing up to 1, 000 million tons annually [8], much is wasted or burnt, causing environmental harm [9]. Therefore, assessing rice straw's gasification potential is crucial for process efficiency and economic viability. Gasification studies using rice straw have shown promising results in terms of gas efficiency and heating value. For instance, A study found that rice straw gasification produces 334 kWh/t with a GWP of 0.642 kg CO_2 - eq/MJ, 27% lower than on - site burning [10]. With methane mitigation, GWP could drop by 34%, approaching carbon neutrality at 2.78 kg CO_2/kg of rice. Singla et al. [11] used an Imbert downdraft gasifier for rice straw briquettes made from a 90: 10 mix of rice straw and cotton stalks, which showed a 15.21 MJ/kg heating value. One research found that gasifying rice straw in a fluidized bed gasifier produced 61% hot gas and 52% cold gas efficiency, with a syngas heating value of 5.1 MJ Nm^{-3} [12]. These results collectively underscore rice straw's efficacy as a gasification feedstock.

The DRC, a significant rice producer, generates substantial rice straw by - products [13]. Despite this, energy production from rice straw is unexplored in the country. Evaluating the potential for syngas and H2 production from this biomass is essential for the DRC's energy sector. In the DRC, with a population of 102 million, energy access is limited, especially in rural areas, with only a 1% electrification rate, compared to 43.7% in urban areas [14].

This study explores using Congolese rice straw for biofuel and H2 production, addressing the DRC's urgent energy needs and promoting job growth and sustainable farming. Despite its abundance and low cost, rice straw's energy potential is under - researched in Africa. Therefore, the research assesses its viability for syngas and H2 production via gasification, analyzing its composition and the factors influencing syngas and H2 production. This study aims to evaluate the viability of Congolese rice straw for hydrogen and syngas production through detailed biomass characterization and gasification experiments. The outcomes of this study are particularly relevant for improving energy access in the DRC and may contribute to global efforts in transitioning to sustainable biomass - based energy systems.

2. Materials and Methods

2.1 Material and Instruments

Table S - 1 outlines the materials and instruments used in the study's experiments, detailing their models, specifications, and roles, from raw material preparation to physical property assessment. The primary material was rice straw, while the main instruments were the downdraft reactor system, the gas chromatograph (GC), and the TGA analyzer, which are critical for assessing gas and biomass compositions. In contrast, the elemental analyzer gives specific elemental information.

2.2 Measurement and Data Analysis

The method of measurement and data analysis used in this work follows a similar process to that used by Waheed [15], as seen from Eqs S - 1 to S - 9. Each sample was injected three times into the GCs; the gas concentrations were averaged and normalized, obtaining the final product. The GC provided the concentration of permanent gases.

2.3 Preparation of Rice Straw Biomass

Rice straw, harvested from the Oryza sativa L plant in rice fields in the DRC's Upper Uélé Province, specifically around Isiro (Latitude: 2° 46′ North, Longitude: 27° 37′ East, was laid out for sun - drying, a cost - efficient technique that leveraged solar energy to evaporate some of the water content in the samples. The biomass material underwent visual inspection, with large foreign objects such as stones, metal fragments, or substantial non - biomass material manually eliminated. The rice straw was then chopped into smaller sizes using a chaff cutter with a capacity of 1000 kg−1, ground, sieved, and stored in air - tight containers to maintain a uniform composition for future use. The rice straw was milled into smaller particles to increase the surface area. Photographs of the raw rice straw are depicted in Figure 1.

Figure 1: Pile of unclean rice straw in the fields in the DRC

2.4 Gasification system and processes

The gasifier in Figure 2, constructed from a heat - resistant alloy and measuring 72 cm, contained a biomass sample in a crucible located within a metallic chamber. Nitrogen, regulated by a digital controller, acted as a carrier gas. An N - type thermocouple monitored temperatures while air and steam were introduced from the top, with flow rates regulated and measured by digital controllers and meters. A condenser bag collected condensable liquids. Two furnaces with precise temperature controls heated the system: one for steam generation and the main one for the reactor's central area. Five grams of biomass were steamed and heated with nitrogen flow for an hour. The process collected condensable liquids and synthesis gas, with low variation in gas composition observed across three trials (Figure S - 1). A temperature of 700 °C was selected because it enhances tar decomposition into H_2, CO, and CH_4, significantly reducing tar yield and improving syngas quality [16]. Steam gasification was performed at 800 °C, as H_2 production peaked at this temperature during the air gasification trials.

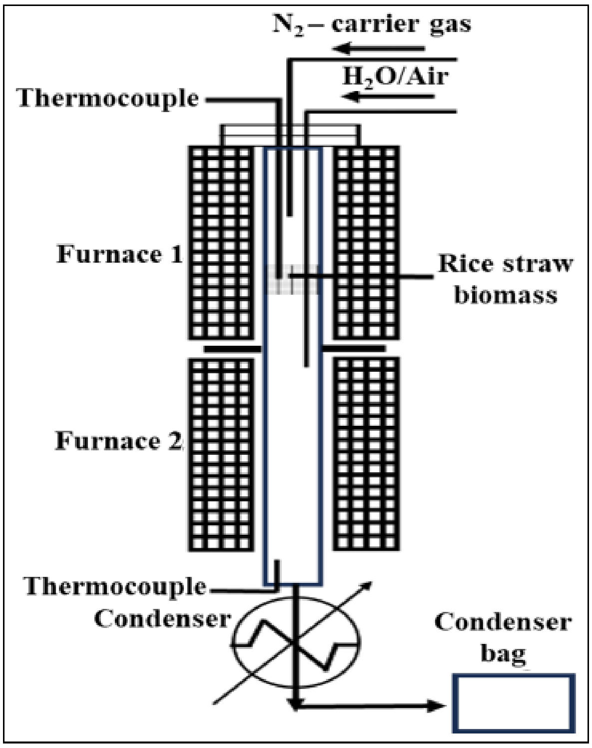

Figure 2: Schematic of the gasification system used in this study

2.5 Biomass characterization and products analysis

The determination of proximate in rice straw biomass was conducted utilizing a Shimadzu TGA - 50H thermogravimetric analyzer (Figure S - 2). The ultimate composition of rice straw biomass was analyzed utilizing the FlashSmart CHNS elemental analyzer (Figure S - 3) to detect carbon (C), H2 (H), nitrogen (N), and sulfur (S) content. Gases generated during gasification were analyzed using gas chromatography (GC) (Agilent 6890N GC/FID GC).

3. Results and Discussion

3.1 Characterization of rice straw biomass

Proximate and ultimate analyses of rice straw were conducted using a thermogravimetric analyzer (TGA) and a CHNS elemental analyzer. The results in Table 1 reveal key insights into the composition of rice straw, including a volatile matter percentage of 68.3%, a fixed carbon content of 12.2%, and a moisture content of 8.4% by weight. The ultimate analysis further highlights the rice straw biomass's carbon, H2, nitrogen, and oxygen compositions at 45.5%, 6.0%, 0.8 %, and 47.7%, respectively, with oxygen concentration determined by difference. These results correspond to the range reported by others [7], [17]. The results for the composition of rice straw highlight the percentage composition of key components: hemicellulose (29.7%), cellulose (36.1%), lignin (14.0%), extractives (9.1%), and ash (11.1%) by weight, which are within the range reported by other researchers [18], [19]. TGA thermograms of rice straw shown in Figure S - 4 show an initial weight loss for up to 100°C attributed to moisture evaporation. Significant weight loss occurs due to hemicellulose and partial cellulose decomposition, forming volatile compounds. This aligns with the highly volatile content observed in rice straw biomass. The DTG curve displays two peaks on the left, likely corresponding to distinct hemicellulosic components as they decompose earlier than cellulose and lignin (around 200°C to 260°C) [20]. The main weight loss peak at approximately 365°C signifies cellulose's thermal breakdown (initiating around 300°C to 350°C) [21] and continuous hemicellulose degradation (up to 350°C to 400°C) [20], indicating overlapping decomposition. Finally, the gradual decomposition across the entire temperature range is attributed to lignin, which persists from around 250°C to 280°C up to approximately 500°C to 600°C [22].

Table 1: Proximate, ultimate biomass composition analyses of rice straw feedstock

Component A	Component B	Component C	Component D
Volatile matter (wt. %)	Fixed carbon (wt. %)	Moisture (wt. %)	Ash (wt. %)
68.3	12.2	8.4	11.1
C (wt. %)	H (wt. %)	N (wt. %)	O[a] (wt. %)
45.5	6.0	0.8	47.7
Hemicellulose (wt. %)	Cellulose (wt. %)	Lignin (wt. %)	Extractives (wt. %)
29.7	36.1	14.0	9.1

[a] Calculated by difference

By analyzing the TGA thermogram (Figure 3A), it was found that higher heating rates shifted the release of volatiles to higher temperatures, likely due to heat transfer limitations. This phenomenon reflects the interplay between heating rate, reaction time, and energy availability in biomass devolatilization processes. Waheed et al. [23] indicated that the impact of heating rate on biomass devolatilization is influenced by reaction time and energy availability, where faster heating necessitates higher temperatures due to shorter reaction times. In comparison, slower heating enables longer residence times and enhances volatile evolution. The DTG thermogram (Figure 3B) suggested an initial moisture loss followed by a considerable mass loss between 225 °C and 430 °C, most likely due to the degradation of hemicellulose and cellulose with the emission of a significant quantity of volatiles.

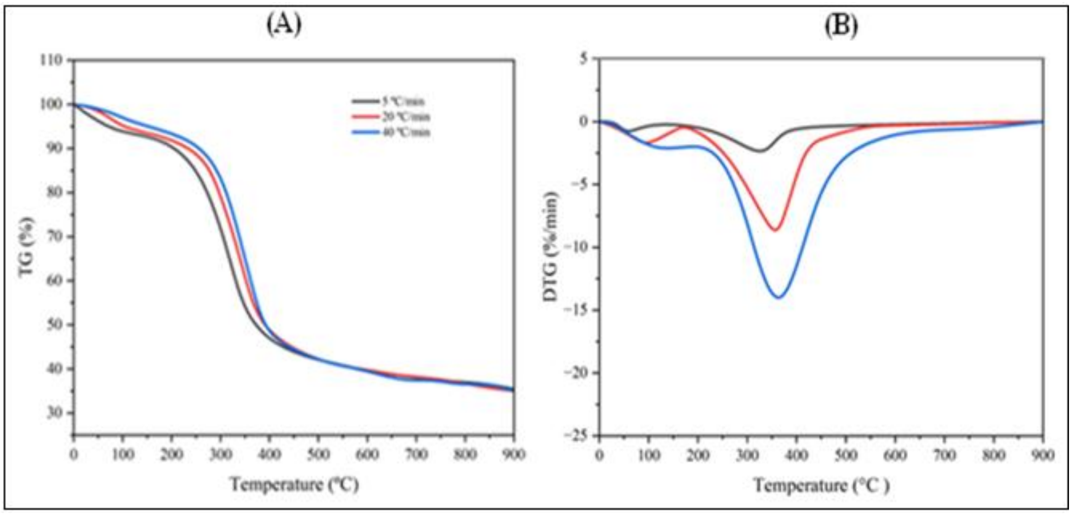

Figure 3: (A) TGA and (B) DTG thermograms of rice straw biomass at 5, 20, and 40 °C/min heating rates

3.2 Air Gasification

3.2.1. Syngas Composition Analysis

To test the potential of Congolese rice straw for syngas and H2 generation, air gasification of the rice straw biomass was conducted at 700°C. The results show the yields were 35.02% solid material, 64.98% gas, and a substantial quantity of H2 (5.07 mmoles/g of biomass), as depicted in Table 2. The high gaseous content from the gasification is likely due to the high hemicellulose content in rice straw [24].

Table 2: Air gasification of rice straw sample

Rice straw product yield	Numerical value
H2 (mmoles/g of biomass)	5.07
Gas/ (biomass) (wt. %)	64.98
Solid/ (biomass) (wt. %)	35.02
H_2/CO	0.92
CO/CO_2	0.77
H_2/CO_2	0.71
H_2/CH_4	2.76
H_2/C_2 - C_4	6.34
CH_4/CO	0.33
CH_4/CO_2	0.26
C_2 - C_4/CO	0.15
C_2 - C_4/CO_2	0.11

The high H2 yield in this study can be explained by the following reactions/equations:

$$Char\ (C) + CO_2 \rightarrow 2CO\ (Boudouard\ Reaction)\ (+172\ MJ/kmol)\ \mathbf{(1)}$$

$$Char\ (C) + H_2O \rightarrow CO + H_2\ (Water - Gas\ Reaction)\ (+131\ MJ/kmol)\ \mathbf{(2)}$$

$$C_mH_n + 2mH_2O \rightarrow mCO_2 + (2m+2n)\ H_2\ (\text{Steam} - \text{Tar} - \text{Reforming Reaction})\ \mathbf{(3)}$$

$$CO + H_2O \rightarrow CO_2 + H_2\ (Water - Gas - Shift\ Reaction)\ (-41\ MJ/kmol)\ \mathbf{(4)}$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O\ (Methanation\ Reaction)\ (-75\ MJ/kmol)\ \mathbf{(5)}$$

$$CH_4 + H_2O \rightarrow CO + 3H_2\ (Steam - Methane - Reforming\ Reaction)\ (+206\ MJ/kmol)\ \mathbf{(6)}$$

The gasification of rice straw biomass at a temperature of 700 °C resulted in an N2 - free syngas composition predominantly consisting of H2 (24.92%), CO (27.01%), and CO2 (35.10%), with lesser amounts of CH4 (9.04%), and C2 - C4 hydrocarbons (3.93%) as seen in Figure S - 5. The significant presence of CO can be attributed to the effective decomposition of cellulose and hemicellulose components within the biomass, favoring the Boudouard Reaction (Eq.1) at the specified temperature. Cellulose and hemicellulose are highly combustible components of biomass, contributing to the volatile matter in the biomass, while lignin primarily forms solid char [25]. There is also a significant amount of hydrogen produced from the rice straw, which could likely be due to the moisture content, H/C ratio of the rice straw biomass, and the high temperature of gasification, which could favor the Water - Gas Reaction (Eq.2) and Steam Reformation of tar (Eq.3). Dong et al. [26] studied the effect of moisture content on municipal solid waste pyrolysis and gasification at 650 °C, reporting that an increase in moisture content increases the hydrogen concentration of syngas to a certain point. In the current study, the moisture content was 8.4% by mass of biomass. Although this is not a high value, it might have synergized with the high temperature and hydrogen content to yield the high hydrogen volume observed in this work.

3.2.2. Effect of Temperature on Syngas Composition

In Figure S - 6, changes in syngas composition were caused by temperature rise (600 - 900 °C), with yields decreasing for C2 - C4, CH4, and CO2 and increasing for CO and H2. The yield of H2 rose from 19.31% at 600°C to 25.30% at 800°C and then fell to 23.75% at 900°C, suggesting that the optimal temperature for H2 production was 800°C, and all subsequent experiments were conducted at this temperature.

This trend suggests that higher temperatures favor the production of CO and H2, which are key components in syngas production, while reducing the presence of CH4 and CO2 in the gas product. The decline in the concentrations of C2 - C4 and CH4 suggests that higher temperatures promote the breakdown of these heavier hydrocarbons into simpler molecules, while for CO2, it could be due to the endothermic reactions consuming CO2, such as the reverse Water - Gas Shift Reaction (Eq.4), becoming more favorable at higher temperatures. The increase in CO most likely resulted from Eq.1, where CO2 reacts with carbon to form CO, and also due to the decomposition of heavier hydrocarbons, as discussed elsewhere in this text. The rise in H2 concentration is most likely due to the partial oxidation of hydrocarbons. However, the subsequent lower H2 content at 900°C onward might be due to the higher gasification rates and shift in the equilibrium of various reactions at this higher temperature, possibly favoring the formation of other products. Specifically, Eq.4, which is exothermic, shifts to the left and becomes more favorable for H2 consumption. It has been reported that the optimal condition for the production of H2 from the air - steam pyrolysis/gasification of biomass was maximized at 800°C [26], beyond which the equilibrium shifts and the reaction rate for H2 production decreases, leading to a lower H2 concentration in the syngas [27]. The exact temperature at which the (H2) concentration begins to drop can vary based on the biomass type, gasifier design, and operational conditions such as steam - to - biomass ratio and equivalence ratio [28]. These findings are supported by research conducted by Waheed et al. [29], who investigated the impact of temperature on gas yields during the pyrolysis/gasification of waste biomass. The study revealed that increased temperature led to higher overall gas yield and increased H2 gas concentration, with a decrease in CH4 and CO2. Similarly, Shahbeig et al. [30] explored the exergy sustainability analysis of biomass gasification. They highlighted that char reacts with CO2 at high temperatures to produce more combustible gases such as CO, leading to greater weight loss.

3.3 Steam Gasification

3.3.1. Syngas Composition Analysis

Figure 4 indicates the syngas composition for the steam gasification of rice straw. The syngas is composed of C2 - C4 (3.76%), CH4 (7.79%), CO2 (11.93%), CO (34.08%), and H2 (43.43%) by volume which agrees with the typical composition of syngas produced from steam gasification of biomass [30 - 50% H2, 25 - 40% CO, 8 - 20% CO2, and 6 - 15% methane] [31]. Nevertheless, compared to their proportion for air gasification above, H_2 in the syngas is relatively higher than that of CO obtained during steam gasification. Eqs 2 and 4 cause high H_2 levels in syngas during steam gasification. As a reactant, Steam stimulates these processes by promoting H_2 and CO production. Conversely, air gasification occurs in the absence of steam, limiting these processes and resulting in less H_2 in the syngas [32], [33].

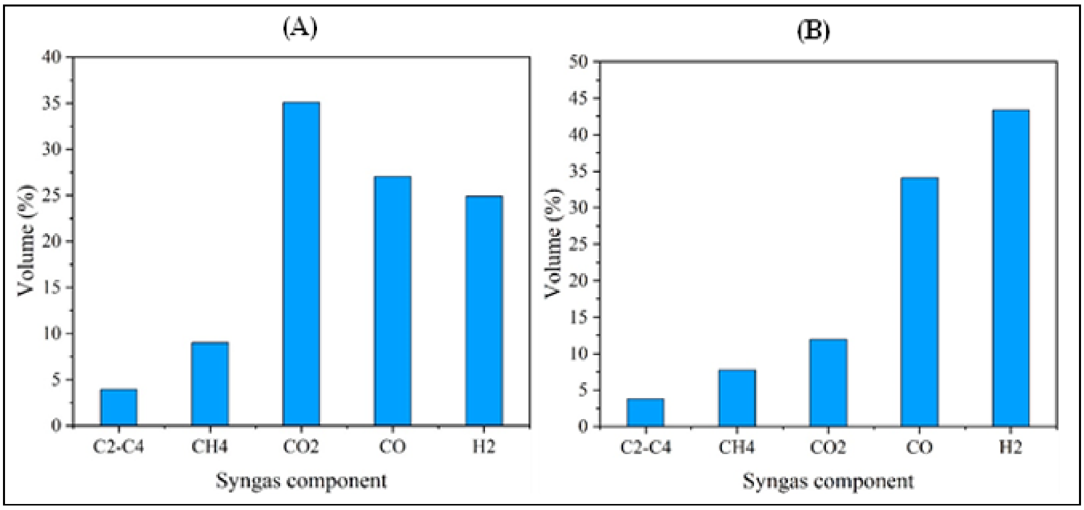

Figure 4: Syngas composition: (A) from air gasification[at]Temperature = 700 °C (B) from steam gasification[at]Temperature = 800 °C and steam flow rate = 5 ml/hr of rice straw biomass. For both, particle size = 1.3 - 3.0 mm, N_2 - flow rate = 100 ml/min, and moisture content = 8 wt%

3.3.2. Effect of Particle Size on Syngas Composition

Figure 5 shows how particle sizes of 0.2 - 0.5 mm, 0.5 - 1.0 mm, 1.3 - 3.0 mm, and 3.0 - 3.5 mm affect syngas composition. The obtained data show that increasing the particle size in biomass steam gasification increases the output of heavier hydrocarbons C_2 - C_4 (1.7% - 6.29%) and methane CH_4 (3.84% - 9.04%). At the same time, the production of emissions is reduced for CO_2 (13.16% - 10.24%), H_2 (46.02% - 42.02%), and CO (35.28% - 32.41%). This suggests that rising C_2 - C_4 and CH_4 at large particle sizes can be explained by particles passing through the gasifier for a longer residence time, producing more complex hydrocarbon chains that are then converted to these gases [34]. CO_2, H_2, and CO decrease with larger particle sizes, possibly because larger particles have a lower surface area - to - volume ratio, slowing the reaction rates that generate these components [35]. Furthermore, greater temperatures and faster reactions promote H_2 and CO generation. Smaller particles, with a larger surface area relative to volume, would heat up and react faster, producing more H_2 and CO. Research backs up these observations with studies demonstrating that smaller particle sizes improve gasification processes, resulting in larger H_2 yields due to superior reaction kinetics and mass transfer rates. For example, Hernández et al. [36] evaluated the influence of particle sizes in the 0.5 - 8 mm range on syngas composition. They discovered that bigger particle sizes resulted in lower syngas output due to the reduced total surface area available for gasification.

Similarly, Kuo et al. [37] investigated the effect of various fluidization and gasification parameters on syngas composition and heavy metal retention in a two - stage fluidized bed gasification process. They discovered that a small particle size of 0.46 mm in the fluidized bed increased the H_2 content of syngas. The authors ascribe this to the better reaction kinetics and mass transfer rates that come with smaller particle sizes.

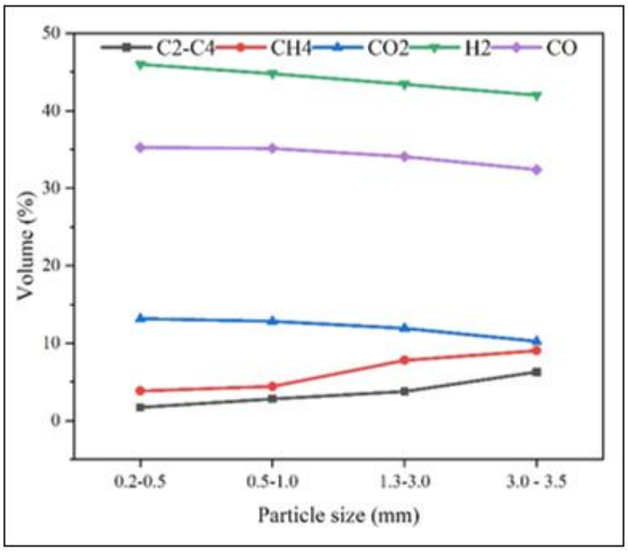

Figure 5: Effect of particle size on syngas composition [at]Temperature = 800 °C, steam flow rate = 5 ml/hr, N_2 - flow rate = 100 ml/min, and moisture content = 8 wt%

The data in Figure 6 shows the effect of steam flow rate on syngas composition during biomass gasification. As the steam flow rate increases from 2.5 to 10 ml/hr, there is a noticeable decrease in the production of C_2 - C_4 (5.83% - 3.48%) and CO (36.25% - 30.04%), while the concentrations of CH_4 (7.34% - 8.25%), CO_2 (9.67% - 14.18%) and H_2 (40.91% - 44.05%) increased. The results in Figure 6 indicate how steam flow rate affects syngas composition during biomass gasification. As the steam flow rate increases from 2.5 to 10 ml/hr, the generation of C_2 - C_4 (5.83% - 3.48%) and CO (36.25% - 30.04%) decreases, but the concentrations of CH_4 (7.34% - 8.25%), CO_2 (9.67% - 14.18%), and H_2 (40.91% - 44.05%) increase. The decrease in C_2 - C_4 hydrocarbons with higher steam flow rates could be due to the Steam Reforming Reactions (eqs 3 and 6), where steam reacts with hydrocarbons to produce CO and H_2, thus reducing the heavier hydrocarbons [15]. However, some of the CO generated is consumed in Eq.4, where CO reacts with steam to produce CO2 and H2, thus explaining the increasing concentrations of H2 and CO2 as the steam flow rate increases. Although Eq.4 is exothermic and higher temperatures do not promote H2 production, the application of Le Chatelier's principle dictates that increased water concentration caused by increased steam flow rates be used to favor H2 generation. Marcantonio et al. [38] reported a decrease in methane concentration as the steam - to - biomass ratio increased. This is contrary to the result observed in this study, which showed a slight increase in the methane concentration with an increased steam flow rate. This increase is likely due to the Methanation Reaction (Eq.5) occurring in the gaseous mixture.

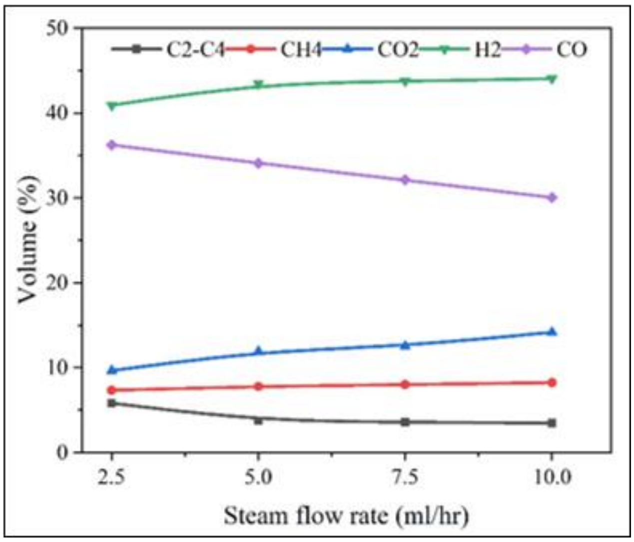

Figure 6: Effect of steam flow rate on gas composition [at]Temperature = 800 °C, rice straw particle size = 1.3 - 3.0 mm, N2 - flow rate = 100 ml/min, and moisture content = 8 wt. %

3.3.4. Effect of N2 - Flow Rate on Syngas Composition

Figure 7's data reveals that the syngas composition remains relatively constant with an increase in the carrier (nitrogen) gas flow rate during the steam gasification of rice straw. For instance, there has been a rise in nitrogen flow rates from 100 ml/min to 400 ml/min. The H2 levels remain at ~43%. Waheed reported similar results, indicating that increasing the nitrogen flow rates does not show any improvement in gas composition, with H2 concentration remaining relatively constant at ~59 vol. % for all nitrogen flow rates from 50 to 400 ml/min [15]. This is most likely due to the inertness of nitrogen, which does not chemically alter the syngas [39]. Insignificant changes in gas concentrations suggest that nitrogen's primary role is environmental, affecting the reaction space rather than the reactions themselves. The H2 content experiences a slight increase with higher N2 flow rates up to 300 ml/min, most likely due to a slight reduction in temperature caused by the entry of more material in the gasifier, shifting Eq.4 equilibrium towards a slight increase in H2 production. It is well known and explained elsewhere in the current study that the water gas shift is an exothermic reaction, and lowering the temperature favors the forward reaction (H2 production). However, at 400 ml/min, the H2 levels drop to previous levels, most likely because the excessive nitrogen dilutes the gas mixture, reducing reaction rates [40]. Hence, nitrogen's primary function is to carry biomass through the gasifier and maintain an oxygen - free environment, essential for preventing combustion without significant reactions with syngas components.

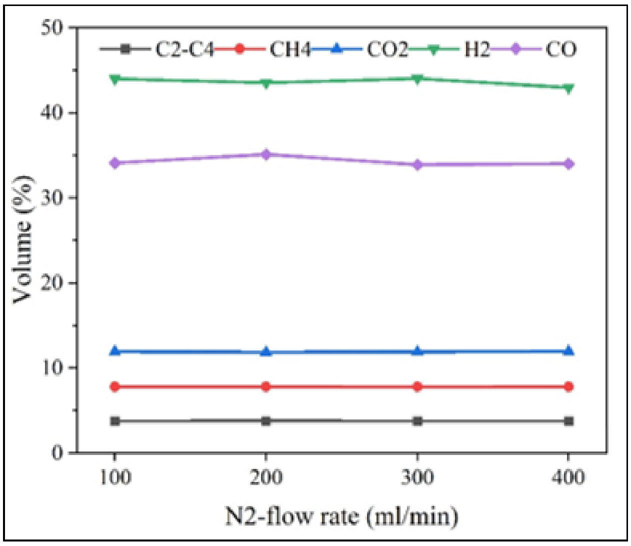

Figure 7: Effect of N2 - flow rate on syngas composition [at]Temperature = 800 °C, rice straw particle size = 1.3 - 3.0 mm, steam flow rate = 5 ml/hr, N2 - flow rate = 100 ml/min, and moisture content = 8 wt%

3.3.5. Effect of Moisture Content on Syngas Composition

Figure 8 shows how the syngas composition from steam gasification of rice straw varies with moisture content from 8% to 20%. The findings show that when the moisture content in the rice straw grows, there is a general pattern of increased CO2 (11.93% - 20.81%), a decrease in H2 (43.50% - 39.35%) and CO (34.08% - 28.05%), and a relatively consistent quantity of C2 - C4 and CH4 levels in the syngas composition. These patterns are consistent with the predicted results of the steam gasification process. For example, Ngamchompoo [7] observed a negative influence on CO concentrations (15.75% - 9.67%) and H2 (7.29% - 5.22%) but a favorable effect on CO2 (16.9% - 18.4%). These authors noted that increasing moisture content greatly lowers the temperature in gasification reactors, slowing reaction kinetics and favoring backward reactions of eqs 1 and 2, resulting in the generation of CO2 at the expense of H2 and CO. This decrease in temperature can be explained by the fact that increasing moisture content needs more energy to evaporate the water, which lowers the gasification temperature and shifts the balance away from H2 generation [41]. The slight changes in C2 - C4 and CH4 are related to the intricacy of the gasification process, in which moisture affects several reactions differently.

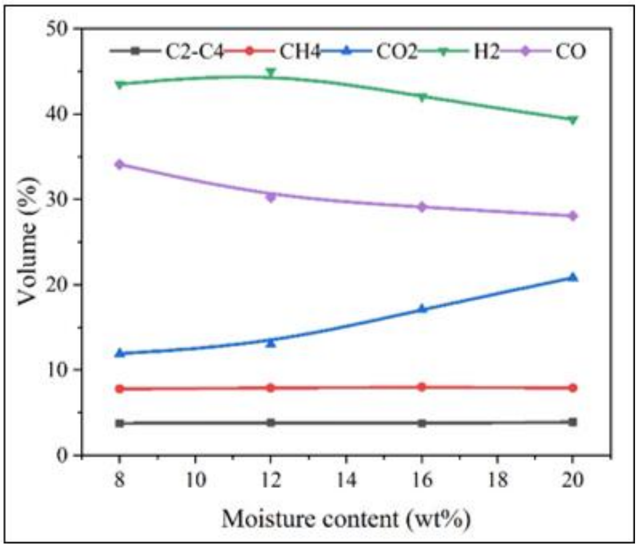

Figure 8: Effect of moisture content on syngas composition [at]Temperature = 800 °C, rice straw particle size = 1.3 - 3.0 mm, steam flow rate = 5 ml/hr, and N2 - flow rate = 100 ml/min

However, it should be noted that while the overall trend in H2 generation was a decrease in concentration with an increase in moisture content, there was an initial increase in H2 concentration from 43.50% to 45.00%, with an increase in moisture content from 8 - 12%. Ngamchompoo [7] observed a similar phenomenon, with H2 concentrations rising from 7% to roughly 10.5% and moisture content rising from 9% - 15% before dropping. The initial rise in H2 levels with increased moisture content can be attributed to the steam reforming processes (Eqs 3 and 6), which occurs when water (in the form of steam) combines with carbonaceous material in biomass to generate H2 and CO. Endothermic reactions occur at a high temperature present at the beginning of the gasification process. However, as more steam is supplied, Eq.4 takes priority, and the generated CO interacts with water vapor to produce CO2 and further H2. This is corroborated by increasing CO2 and H2 concentrations and decreasing CO levels between 8% and 12% moisture content. As described earlier, the subsequent decrease in H2 levels occurs when additional water lowers the temperature.

3.3.5. Optimized Syngas Composition

The optimized syngas is composed of C2 - C4 (3.83%), CH4 (7.90%), CO2 (13.05%), CO (30.22%), and H2 (45.00%) by volume at temperature of 800 °C, rice straw particle size of 1.3 - 3.0 mm, steam flow rate of 5 ml/hr, and N2 - flow rate of 100 ml/min. However, Table 3 shows the yields of product and H2 from the steam gasification of five grams of rice straw biomass. The gasification procedure produced 63.30 wt. % of gas from rice straw, adjusted for the absence of input water. A higher output of H2 was recorded, mainly owing to the initial step of gasification, which involved processing volatiles and tars from the biomass. The production of H2 was 17.97 mmoles/g of rice straw, indicating a significantly high output. This high yield highlights the gasification method's efficiency. Numerous research studies on the steam gasification of rice straw have consistently found higher H2 levels. For instance, Parvez et al. [42] simulated air, steam, and CO2 - enhanced gasification of rice straw and evaluated their energy, exergy, and environmental implications, finding that steam gasification resulted in higher H2 levels.

Table 3: Steam Gasification of Rice Straw Sample

Rice straw product yield	Numerical value
H2 (mmoles/g of biomass)	17.97
Gas/ (biomass) (wt. %)	68.30
Solid/ (biomass) (wt. %)	31.70
H_2/CO	1.49
CO/CO_2	2.32
H_2/CO_2	3.45
H_2/CH_4	5.70
$H_2/C_2 - C_4$	11.75
CH_4/CO	0.26
CH_4/CO_2	0.60
$C_2 - C_4/CO$	0.13
$C_2 - C_4/CO_2$	0.29

Conditions: at 800°C, 100 ml/min nitrogen flow rate, particle size of 1.3 - 3.0 mm, steam injection rate of 5 ml/h, and 12% moisture content

Similarly, Babatabar and Saidi [43] investigated H2 generation via steam gasification of several biomass types, including rice husk, and emphasized higher concentrations of optimizing H2 produced. On the other hand, the thermodynamic advantage of steam gasification stems from its endothermic processes, which promote H2 synthesis from biomass with the aid of the high gasification temperatures in this study. Furthermore, in situ CO2 collection during gasification alters the reaction equilibrium, increasing H2 generation. Moreover, lignocellulosic biomass rich in hemicellulose, such as the rice straw used in the current study, increases syngas H2 levels due to hemicellulose's higher reactivity and capacity to enlarge the surface area for steam [44], [45], hence enhancing H2 - generating processes.

In contrast, Waheed et al. [15], [29] found a greater H2 output of 23.71, 21.18, and 21.59 mmoles/g of biomass in rice husks, sugarcane bagasse, and wheat straw, respectively. Aside from the variations in biomass types, the higher results might be attributed to the ultra - high temperature (950°C). However, producing significant H2 at a lower gasification temperature could suggest a more energy - efficient and cost - effective technique. Lower temperatures reduce energy consumption and costs and may also extend equipment life, making the technology more suitable for large - scale applications. Hence, despite lower yields as compared to higher temperatures, increasing efficiency is crucial for long - term biomass gasification.

Typically, the higher heating values (HHVs) for a majority of lignocellulosic biomass materials fall within the range of 15–19 MJ/kg [46], reflecting the substantial energy potential they hold. However, steam pyro - gasification is usually at the higher end of this range due to the higher H2 content. Table S - 2 provides theoretical estimates of HHVs of the rice straw used in the current work from its proximate and ultimate values using different models. The table shows that the HHV values range from 15.27 to 18.37 MJ/kg, well within the range of lignocellulosic biomass.

As seen in Table S - 3, the study's findings are significant, showing 24.92% and 45.00% H2 production from rice straw gasification at 700°C and 800°C, respectively, without a catalyst. This contrasts with the other studies that used catalysts to achieve between 55.65% to 79.77% H2 volume. The inherent ability of the biomass to produce H2 suggests that adding a catalyst could yield even higher results, underscoring the need for further research into the use of minimum catalyst for cost - effective and sustainable H2 generation.

4. Conclusion

Experiments on the steam gasification of Congolese rice straw were conducted in a fixed - bed reactor to produce hydrogen - rich syngas. The results indicate that rice straw, with a high volatile matter content (68.3%) and carbon composition (45.5%), yields a substantial amount of gas during thermal decomposition. The distinct breakdown phases of hemicellulose, cellulose, and lignin contribute meaningfully to gas generation and confirm the biomass's suitability for gasification.

Significantly, hydrogen concentrations of 24.92% and 45.00% were achieved at 700 °C and 800 °C respectively, without the use of a catalyst. This highlights the rice straw's inherent capacity to produce hydrogen, with potential for even greater yields if catalysts are incorporated—an area warranting further investigation for cost - effective and sustainable hydrogen production.

Enhancing syngas quality and H_2 output was closely linked to process parameters. Smaller biomass particles accelerated reaction kinetics and improved hydrogen yields, while larger particles favored the production of heavier hydrocarbons and methane. Similarly, increased steam flow promoted steam reforming reactions, boosting H_2 and CO_2 levels, though excessive moisture content negatively impacted syngas quality by lowering the reactor temperature and slowing reaction rates.

In summary, this study confirms the viability of Congolese rice straw as a renewable feedstock for hydrogen generation via steam gasification. Optimizing operating conditions such as temperature, particle size, and steam flow rate significantly improves gas quality and hydrogen output. These insights present a compelling case for deploying rice straw - based gasification systems in rural Africa as part of a broader green energy initiative. The findings offer practical implications for the DRC's energy strategy by supporting a transition toward decentralized, biomass - based, low - carbon energy solutions.

Supplementary Materials are available at: ***https: //docs. google. com/document/d/1M3 - w9j3hxg6y9YQzBOcyUJpHSzMbPiG3lZhFvY4qvms/edit?tab=t.0***

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