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Experimental investigation of process parameters for hydrogen-rich syngas production from rice husk gasification

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ABSTRACT

The overconsumption of conventional fossil fuel by the energy and petrochemical sectors demands for the development of alternate renewable sources. Biomass is found to be an effective alternate renewable energy source for the carbon-neutral production of energy and chemicals. Rice husk, one of the most common and abundant lignocellulosic biomass in Asia, is used in the present work as potential feedstock for the thermo-chemical conversion through gasification process in a lab-scale fixed bed (downdraft) reactor. In this work, the influence of various parameters such as the physico-chemical properties of the biomass, the temperature of gasifier, the size of the particles, the steam flow rate, equivalence ratio (ER) and gasifying agents such as mixture of (air + steam) and steam alone were investigated. The (air + steam) mixture at an ER of 0.27, steam flow rate of 0.775 $ml.min^{-1}$, and the reactor temperature at 950 °C, yielded the highest hydrogen of ~40 % (vol.) and carbon monoxide of ~12 % (vol.) with a high heating value (HHV) of ~7 $MJ.m^{-3}$. In contrast, when the experiments were conducted using steam alone as the gasifying agent at an ER of 0.24 with steam flow rate 0.6 $ml.min^{-1}$ and the reactor temperature 950 °C, the produced syngas reported to have a HHV of ~11 $MJ.m^{-3}$ with hydrogen and carbon monoxide content of ~70 % (vol.) and ~10 % (vol.), respectively. The outcome shows that steam is a better gasifying agent for production of hydrogen rich syngas as compared to the (air + steam) gasifying mixture. The results also show that higher temperature favors hydrogen production however, a significant decrease in the HHV of the syngas was observed at elevated temperatures. Furthermore, the hydrogen conversion efficiency and energy conversion efficiency were calculated and were found to be 81 and ~70 %, respectively. Consequently, the produced syngas has the potential to be utilized as a renewable fuel in the industrial sector.

1. Introduction

The global dependence on conventional fossil fuel by the energy and petrochemical sectors resulted in its overconsumption. The subsequent release of CO_2 from the transportation system challenges the earth ecosystem by increasing the global warming. Biomass is found to be an effective alternate renewable energy source for the carbon-neutral production of energy and chemicals [1]. Moreover, for a sustainable process, the biomass feedstock should be available in sufficient amount to meet the outgrowing demand of the energy and fuel industries. In addition, the most important factor for biomass feedstock selection is the quality of the produced biofuel and the extent to which further upgrading is required to make them suitable for different kinds of applications. The yearly global production of biomass amounts to approximately 146 billion tons, with carbon constituting around 20 billion tons. It is estimated that about 25 % of the world's energy demand can be met by biomass waste, making biomass a key component of the energy supply [2]. As per FAOSTAT 2022, global rice production in 2023 was approximately 800 million tons, with India being the second-largest producer after China, with an 18.75 % share. It has also been reported that each kilogram of milled rice generates 0.28 kg of rice husk, potentially accounting around 58 million tons of rice husk produced in India [3]. Since, the rice husk has a low bulk density and a high content of amorphous silica. Their disposal by landfilling creates perturbation and eutrophication in the terrestrial and aquatic ecosystem. High silica content during their combustion forms suspended crystalline particles that cause environmental pollution and health risks. Nevertheless, the rice husks can be utilized as a suitable source of

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alternate energy besides the current available energy [4]. It can also play a significant role in decarbonizing the energy, transport and agriculture sectors.

Gasification is an efficient and robust thermochemical conversion process that produces syngas, solid biochar, and a small amount of tar from second-generation lignocellulosic biomass. In a gasifier, biomass feedstock is transformed into a mixture of combustible and non-combustible gases known as synthesis (syn) gas, condensable liquid (tar) and solid by-product (ash). Fixed bed gasifiers can be classified into updraft, downdraft and cross draft according to the biomass feeding system and the syngas flow in the gasifier [5,6]. The biomass feedstock is fed into a downdraft gasifier from the top and produced syngas flows downward while going through the processes of drying, pyrolysis, oxidation, and reduction. Syngas, the result of gasification, leaves the gasifiers via a gas outlet located at the bottom of the reactor [7]. Syngas often consists of a combination of combustible gases like CO, H_2, and CH_4 and non-combustible gases like CO_2 and N_2 [8]. Indicators of syngas quality include tar content and heating value. High heating value (HHV) and low tar content are referred as a high-quality syngas. Some significant factors, including the characteristics of the biomass, the process parameters, and the design of the gasifiers, have an impact on the quality of the syngas produced from biomass gasification [9,10]. Particle size, density, elemental composition (C, H, O, and N, which are derived from ultimate analysis), fixed carbon, volatile matter, ash content, and moisture content (obtained from proximate analysis) are all features of biomass that must be taken into account during gasification [11,12]. Equivalence ratio (ER), gasification temperature, and biomass consumption rate are the operating parameters of the gasification process [13]. Syngas produced during the gasification of biomass can be used as fuel for IC engines or gas burners. Downdraft gasifiers are typically better suited for small-scale applications with a thermal capacity of 10 kW to 1 MW. Due to its simplicity in construction and operation as well as the low tar content of the produced syngas, downdraft gasifiers are particularly preferred [14,15].

This work demonstrates the gasification of rice husk in a fixed bed reactor (downdraft gasifier) at a lab scale set-up. The present study aims to produce hydrogen-rich syngas and investigate the influence of various parameters such as the physico-chemical properties of the biomass, the temperature of gasification, the size of the particles, the steam flow rate, ER and gasifying agents such as mixture of (air + steam) and steam alone are considered. In addition, gasification output is assessed in terms of syngas composition, HHV, hydrogen conversion efficiency and energy conversion efficiency.

2. Experimental methodology

2.1. Feed preparation and characterization

Rice husk, obtained from a local vendor (Rupnagar, Punjab) was used as the feedstock. The rice husk was pre-treated by washing, drying, and grinding and sieving to achieve different particle size of 0.1, 0.125, 0.5, 0.85 and 1.18 mm. The moisture, volatile matter, and ash contents of the solid biofuel (rice husk) were determined using BS EN 14,774–3:2009, BS EN 15,148:2009, and BS EN 14,775:2009 methods, respectively. The elemental analysis of the sample was carried out by Thermo Scientific Flash 2000 Organic Elemental Analyzer. The thermal conversion of rice husk was examined by using thermogravimetric analysis (TGA/DTG) Instruments SDT 650. The HHV was calculated theoretically by using the modified Dulong's equation, given in Eq. (1) [16].

2.2. Gasification reactor setup and experimental procedure

The lab scale fixed bed reactor (0.5 m height and 0.04 m diameter) with a throughput capacity of 15–20 g/batch was used to perform gasification of rice husk, shown in Fig. 1. The gasification reactor consisted of the following subparts: gas preheater, fixed bed reactor, reactor furnace, peristaltic pump, condenser, gas-liquid separator and liquid fraction collector. The reactor was externally heated independently, and the temperatures were regulated with PID controllers. Temperature of reactor is monitored using two K-type thermocouples located at top and bottom portion of the reactor. The biomass was fed manually into the fixed bed reactor prior to the experiment. The preheated steam at 150 °C was used as a gasifying agent with a flowrate of 0.2–0.95 $ml.min^{-1}$. It was passed at the desired flow rate through the reactor. The vapor residence time was in the range of minute to partial/complete cracking of the vapors prior to condensation. The produced gaseous products left the reactor and passed through a condenser that was connected to the reactor exit to capture the condensable vapors (tars) and then through a cotton filter to remove particulate matter and biochar from the outgoing gas streams before passing through online gas chromatography. The condensed vapor from the condenser was separated and collected from the gas-liquid separator. The uncondensed vapors were further passed through the online gas chromatography to analyze of the gaseous product. The composition of gaseous products (hydrogen, carbon monoxide, carbon dioxide, nitrogen, oxygen and methane) was analyzed using gas chromatography thermal conductivity detector (GC-TCD, Agilent technologies GC-7820A) equipped with packed columns (HayeSep,T, HayeSep Q and Molecular sieve 5A) having dimensions of 1.5 m L × 2 mm ID × 0.25 μm df. with argon as carrier gas. Calibration was performed to calculate the producer gas composition using relative response factors of the gaseous components that are found in gas product. The liquid product obtained from gas liquid separator mainly contains the organic / aqueous phase of the bio-oil were also analyzed by gas chromatography (GC-TCD, Agilent technologies GC-7820A) equipped with DB-5 capillary column with flame ionization detector (FID). The effect of temperature, particle size, steam flow rate, air flow rate, ER, and steam to biomass ratio on the produced gas was investigated by conducting the reactions in the temperature, particle size and steam flow rate range of 500–950 °C, 0.1–1.18 mm and 0.2–0.95 $mL.min^{-1}$, respectively. At the end of the experiment, by-product biochar (and ash) was removed from the reactor. All the experiments were repeated thrice to guarantee the consistency of data.

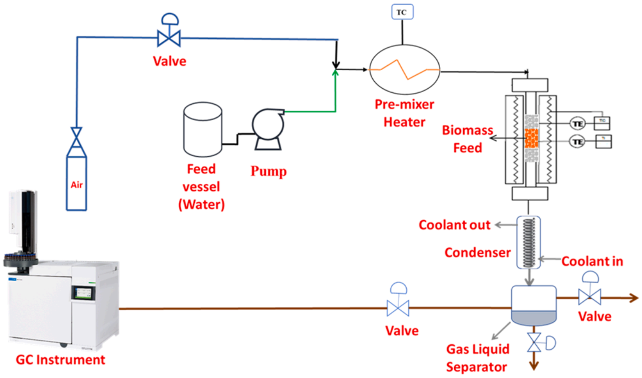

Fig. 1. Schematic of experimental set up.

The HHV, and the ER were estimated by using Eq. (1) and Eq. (2), respectively.

$$(HHV)_{Syngas} = \frac{(X_1.\mathrm{HHV})_{CO} + (X_2.\mathrm{HHV})_{H_2} + (X_3.\mathrm{HHV})_{CH_4}}{100} \tag{1}$$

X_1, X_2, and X_3 represent the volume % of the combustible gases CO, H_2, and CH_4 found in the produced syngas, which can be determined through Gas Chromatograph analysis. Table 1 displays the heating values associated with CO, H_2, and CH_4. [17]

The Equivalence ratio is calculated by Eq. (2)

Table 1
Heating values of CO, H_2, and CH_4.

Compound	**$MJ.m^{-3}$**
CO	12.71
H_2	12.78
CH_4	39.76

$$\mathrm{ER} = \frac{\text{Mass of } O_2 \text{ Required for gasification of biomass}}{\text{Mass of } O_2 \text{ Required for the complete combustion of biomass}} \qquad (2)$$

Where ER is equivalence ratio.

3. Results and discussion

3.1. Thermal behavior of rice husk

The TGA and DTG analysis was performed on rice husk and the result is shown in Fig. 2. The removal of moisture from rice husk started from temperature 110 °C up to 200 °C. The main component of biomass, i.e., cellulose, hemicelluloses, and lignin, which mainly converted into pyrolysis products degrades in the temperature range of 250 °C to 500 °C. Furthermore, the removal of ~60 % of volatile matter takes place during the devolatilization phase. Thermal deterioration in this region transpired through two reaction stages, identifiable by two overlapping DTG peaks. The initial peak (307 °C) associated with the lower temperature shoulder on the left of the DTG curve signifies a rapid weight loss of approximately 50 % occurring between 250 °C and 375 °C, attributed to hemicellulose decomposition, while the subsequent peak (353 °C) indicates cellulose decomposition occurring between the 350 °C and 420 °C. It was difficult to indicate the degradation of lignin because lignin starts to decompose from 200 °C and ends at 900 °C. After the degradation of organic compounds, the leftover was mainly consisted of the fixed carbon and residual (ash).

Heating value of Rice husk is calculated as 13.10 $MJ.kg^{-1}$. The ultimate, proximate, and compositional analyses of rice husk are listed in Table 2.

$$\mathrm{HHV}\ \left(\mathrm{MJ.kg^{-1}}\right) = \frac{33.5\ \times\ \mathrm{wt\%\ C}}{100} + \frac{142\ \times\ \mathrm{wt\%\ H}}{100} - \frac{15.4\ \times\ \mathrm{wt\%\ O}}{100} \qquad (3)$$

When solid biomass is gasified, it produces a gaseous mixture that includes water vapor, residual solids, trace elements, tars like benzene and other aromatic hydrocarbons, hydrogen, carbon dioxide, carbon monoxide, methane and organic vapors. The following explains the basic engineering and reactions involved in the gasification of biomass. Lignocellulose biomass is transformed into volatile gases, char, and tar during the biomass gasification process, as the gasification reaction equation illustrates. The variation in gaseous mixture's composition dependent on a number of factors, such as the gasification conditions, presence of inert and the surrounding environmental factors. Additionally, the inorganic materials found in biomass, such as silicon (Si), aluminum (Al), titanium (Ti), iron (Fe), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), phosphorus (P), sulfur (S), and chlorine (Cl), can be converted into ash through gasification and could be utilized as a fertilzer [18]. It highlights the versality of gasification in addition to its possible significance for waste management and sustainable energy production.

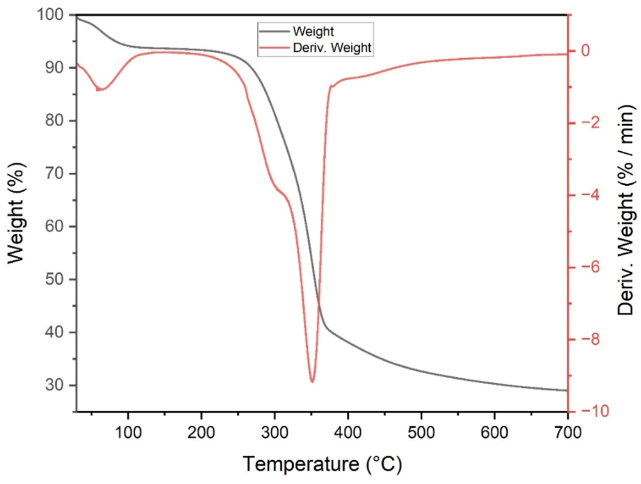

Fig. 2. TGA and DTG analysis of rice husk.

Table 2
Properties of rice husk.

Proximate analysis (dry basis, wt. %)		Ultimate analysis (wet basis, wt. %)		Compositional analysis (dry basis, wt. %)	
Moisture	10.00	Carbon	41.48	Cellulose	40.92
Volatile matter	58.32	Hydrogen	5.18	Hemicellulose	14.16
Ash	14.87	Oxygen	52.90	Lignin	34.25
Fixed carbon	16.81	Nitrogen	0.44	Extractives	10.67
Bulk density (kg m^{-3})	304.9	Sulfur	ND		
Heating value (MJ. kg^{-1})	13.10				

Gaining an understanding of the intricate interactions between these components is essential for enhancing the gasification process and maximizing its potential for a range of commercial and environmental uses. A sequence of distinct thermal processes makes up biomass gasification. Upon heating, biomass undergoes a drying phase, which continues until the temperature approaches 120 °C. Around 350 °C is the temperature at which highly exothermic reactions known as partial oxidation reaction (R**2)** and oxidation (R**1)** occur. A devolatilization process releases the volatile components of the biomass at this temperature range. The leftover solid material, referred to as char, is gasified after this point.

Oxidation reaction	$C + O_2 \leftrightarrow CO_2$	R1
Partial oxidation reaction	$C + 0.5O_2 \leftrightarrow CO$	R2

The chemical components of biomass heated to temperature between 500 and 950 °C in the presence of a gasifying agent. Along with homogeneous volatile reactions (R6-R10) and tar conversion reactions (R11-R15), three gasifying reactions (R3-R5) occur in this temperature range most frequently.

Hydrogenation reaction	$C + 2H_2 \leftrightarrow CH_4$	R3
Boudouard reaction	$C + CO_2 \leftrightarrow CO$	R4
Water gas reaction	$C + H_2O \leftrightarrow CO + H_2$	R5

The heat generated within the gasifier unit itself, most frequently through the exothermic combustion of biomass, or from external sources can power these reactions. The utilization of biomass as a sustainable energy source is contingent upon the intricate process of gasification, which holds potential for diverse industrial application [19]

Steam reforming of methane	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	R6
Water gas shift reaction	$CO + H_2O \leftrightarrow CO_2 + H_2$	R7
Partial oxidation	$CO + 0.5O_2 \leftrightarrow CO_2$	R8
Oxidation	$CH_4 + 2O_2 \leftrightarrow CO + 2H_2O$	R9
Partial oxidation	$H_2 + 0.5O_2 \leftrightarrow H_2O$	R10

The tar composition varies as the gasification process's temperature rises. It moves through phenolic ethers, alkyl phenolics, heterocyclic ethers, polyaromatic hydrocarbons and larger polyaromatic hydrocarbon in specific order, starting with mixed oxygenates. The way in which the chemical reactions change as the temperature rises is demonstrated by this sequence of alterations. A high-temperature tar made of cellulose that has been analyzed shows that levoglucosan is one of the main ingredients [20].

Steam reforming	$C_xH_y + xH_2O \rightarrow xCO + (0.5 + x)H_2$	R11
Partial oxidation	$C_xH_y + 0.5xO_2 \rightarrow xCO + 0.5yH_2$	R12
Dry reforming	$C_xH_y + CO_2 \rightarrow xCO + (0.5y + x)H_2$	R13
Methanation	$C_xH_y + H_2 \rightarrow xCH_4$	R14
Cracking	$C_xH_y \rightarrow 0.25yCH_4 + (x - 0.25y)C$	R15

In addition, the gasification residence time is crucial for the conversion of tar. Greater secondary vapor-phase cracking at higher pyrolysis temperatures is caused by longer vapor residence times, which produces more gases, water, and low-molecular weight compounds char. The rate at which char is generated is dependent on pyrolysis temperature; slower pyrolysis processes yield more char. Nevertheless, the char yield drastically decreases with temperature, particularly above 400 °C. As the temperature rises, the char changes, becoming more aromatic and higher in carbon. This modification is caused by the removal of hydroxyl, aliphatic, carbonyl, and olefinic CC groups. Moreover, voids in the char's pore structure are created by the release of volatile materials at higher gasification temperatures. Higher temperatures can also result in melting, fusing, and softening of the char/inorganic compounds; the aromatization process is represented by a significant contraction of the carbon structure that happens above 500 °C [21,22].

3.2. *Effect of reactor temperature when using (Air+Steam) mixture as gasifying agent*

The temperature plays an important role in the biomass gasification process. In this study, the temperature of the reactor was varied from 500 to 950 °C in increments of 100 °C while keeping all other conditions constant. The results of these experiments are presented in Fig. 3.

Fig. 3. illustrates the impact of gasification temperature (ER = 0.27) on the syngas composition of pretreated rice husk. As the temperature of the gasification process is increased from 500 to 950 °C, the concentration of the hydrogen increases from 31.38 to 39.17 vol (%). Simultaneously, the concentration of the carbon monoxide improves from 5.97 to 11.72 vol (%). These trends attribute to Le Chatelier's principle that higher temperatures are favourable to the products in endothermic processes and the reactants in exothermic reactions. In addition, both the Boudouard reaction ($C + CO_2 \rightarrow 2CO$) and the endothermic water-gas reaction ($C + H_2O \rightarrow CO + H_2$) are responsible for the rise in hydrogen and carbon monoxide [23]. Increased temperature causes both reactions to become more prevalent, which encourages the production of more carbon monoxide and hydrogen. At lower temperatures, the water-gas shift reaction ($CO + H_2O \leftrightarrow CO_2 + H_2$) predominantly leads to the production of carbon dioxide. However, at higher temperatures (>700 °C), the produced carbon dioxide is subsequently consumed by the Boudouard reaction ($C + CO_2 \rightarrow 2CO$) to generate more carbon monoxide gas. In contrast, gasification temperature has a neglible effect on methane yield, which remains steady over the tested temperature range. The reason is that, methane is primarily produced during devolatilization process $\left(C_xH_y + H_2 \rightarrow xCH_4\right)$, but it is then consumed by the methane dry reforming reaction ($CH_4 + CO_2 \rightarrow 2CO + 2H_2$) at higher temperature (>1000 °C). This justifies the constant level of methane concentration in syngas over the tested temperature range in this study.. As shown in Fig. 3, the HHV of gaseous products increase as temperature rises, mainly due to increase concentrations of hydrogen and carbon monoxide. It is evident that the elevated temperatures favor steam reforming, the Boudouard reaction and thermal cracking of tar, explaining the observed increase in hydrogen and carbon monoxide concentrations in the syngas.

3.3. *Effect of equivalence ratio when using (Air + steam) mixture as gasifying agent*

The study also investigated how changing the ER from 0.21 to 0.41, while maintaining a constant gasification temperature of 950 °C, affects the composition of syngas. Fig. 4 clearly shows that an increase in ER leads to a reduction in the production of hydrogen and carbon monoxide. However, a higher ER results in an increase in carbon dioxide. This occurs because increasing the ER allows more oxygen to enter the fixed bed gasifier, enhancing the oxidation reactions for both hydrogen ($H_2 + 0.5O_2 \leftrightarrow H_2O$) and carbon monoxide ($CO + 0.5O_2 \leftrightarrow CO_2$). Therefore, higher ERs favor carbon dioxide at the expense of hydrogen and carbon monoxide. When ER is increased from 0.21 to 0.41, the methane concentration decrease slightly, as shown in Fig. 4. This is because methane oxidizes ($CH_4 + 2O_2 \leftrightarrow CO_2 + 2H_2O$), when it reacts with oxygen to form carbon dioxide and water. Additionally, the HHV decreased significantly from 7.39 to 4.81 MJ.m^{-3} as the ER increased from 0.21 to 0.41.

3.4. *Effect of steam flow rate ratio when using (Air + steam) mixture as gasifying agent*

The syngas composition at various (air and steam) mixture flow rates at the reactor temperature of 950 °C is presented in Fig. 5. It is evident that when the flow rate of the (steam and air) mixture increases from

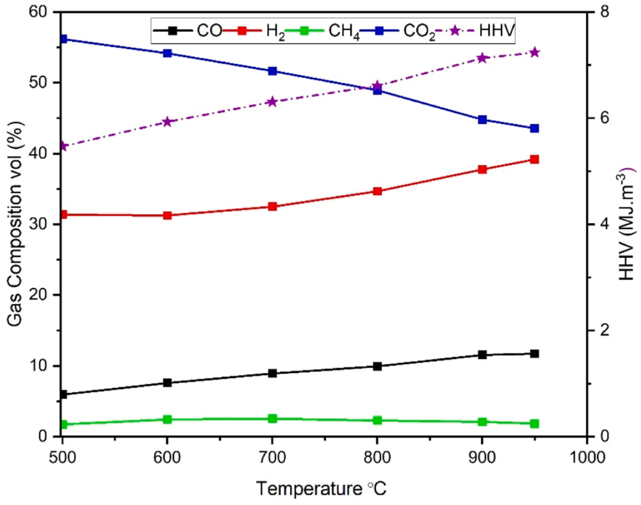

Fig. 3. Effect of temperature on gas composition(vol%) of rice husk, when using mix of (Air+Steam) as gasifying agent.

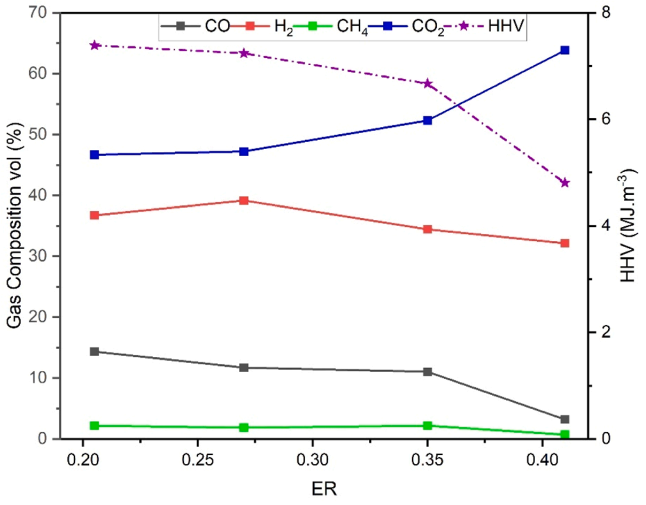

Fig. 4. Effect of ER on gas composition(vol%) of rice husk at 950 °C, when using mix of (Air+Steam) as gasifying agent.

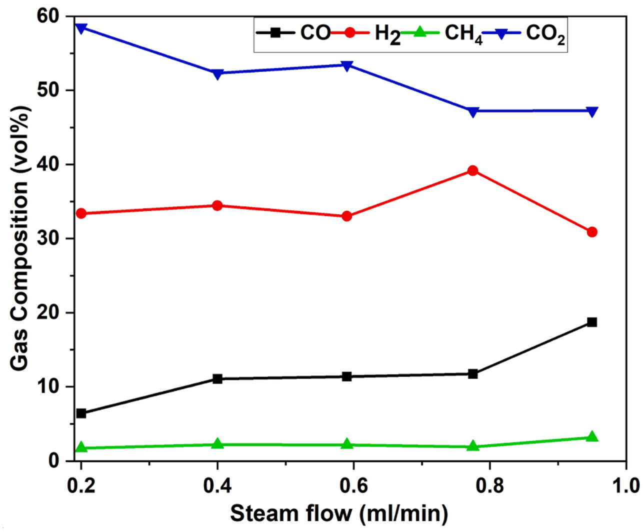

Fig. 5. Effect of mixture of (Air+Steam) flow rate on gas composition(vol%) of rice husk.

(0.2 + 15) mL.min^{-1} to (0.775+15) mL.min^{-1}, a significant increase in the volume fraction of hydrogen in the syngas is observed. This outcome is the result of increasing the flowrate of the mixture (steam and air) which accelerates the oxidation reactions. Since the steam reforming and water-gas shift reactions both are favorable for hydrogen production, leading to higher hydrogen vol (%) in the syngas. In contrast, it is worth to mention that as the (steam and air) mixture flow rate was further increases from (0.775+15) mL.min^{-1} to (0.95+15) mL.min^{-1}, the hydrogen content gradually decreases. This is primarily because of the oxidation reaction between hydrogen and the (steam and air) mixture. Additionally, an increase in the carbon monoxide content is noted, which could be the result of a stronger oxidation reaction between the char (fixed carbon) and the mixture of (steam and air). When the flow rate of the (steam and air) mixture increases from (0.2 + 15) mL.min^{-1} to (0.95+15) mL.min^{-1}, the volume fraction of carbon dioxide decreases while methane concentration increases due to methanation reaction.

3.5. Effect of reactor temperature when using (steam as gasifying agent)

The influence of reactor temperature on the gasification performance of rice husk was investigated between 500 and 950 °C in steps of 100 °C while keeping other parameters unchanged. The results are shown in Fig. 6.

From Fig. 6, it can be observed that hydrogen vol (%) increased from 29.6 to 70.9 % with increasing the temperature 600–950 °C, whereas the vol (%) of methane decreased from 24.6 to 1.4 %. Higher temperatures assist the reactants in exothermic processes and the products in endothermic reactions, according to Le Chatelier's principle. Consequently, there was a significant temperature dependence in the endothermic reactions $CH_4 + H_2O(g) \leftrightarrow CO + 3H_2$ and $CH_4 + 2H_2O(g) \leftrightarrow CO_2 + 4H_2$, which led to a rise in hydrogen vol (%) and a fall in methane vol (%). Char oxidation reaction $C + 0.5O_2 \leftrightarrow CO$, was the primary factor in determining the amount of carbon monoxide in syngas, which decreased from 23.7 to 9.6 % with increase in the temperature from 600 to 950 °C. As shown in Fig. 6, the concentration of carbon dioxide vol (%) decrease firstly and reach the minimum value at 850 °C, and then increases gradually. Since, carbon dioxide reacts with carbon to produce carbon monoxide $C + CO_2 \leftrightarrow 2CO$, and could be attributing to the decrease in carbon dioxide at higher temperature. As shown in Fig. 6, the syngas HHV decreases as temperature rises. In conclusion, it can be recommended that a greater temperature is better for the production of hydrogen-rich syngas.

3.6. Effect of ER on syngas composition when using steam as gasifying agent

Further experiments were conducted using steam as the gasifying agent. This section investigates how changing the ER from 0.17 to 0.65, while maintaining a constant gasification temperature of 950 °C, affects the composition of the produced syngas. The results are shown in Fig. 7.

The impact of ER, which ranges from 0.17 to 0.65, on the syngas composition is examined. It was found that the gasifier temperature increased with an increase in the ER. The result is divided into two categories, which is from the range of ER is 0.17 to 0.24 and above 0.24. Initially, the concentration of carbon monoxide and carbon dioxide decrease from 16.7 to 9.6 vol (%) and from 30.8 to 18 vol (%), respectively with the increase in ER from 0.17 to 0.24. The concentration of hydrogen vol (%) on the other hand increases from 49.7 to 70 % and methane is decreases from 2.7 to 1.8 %, as the dry reforming reaction takes place. Moreover, when the ER is higher than 0.24, the concentration of carbon dioxide was found to rise from 18 to 46.9 vol (%), while the carbon monoxide fell gradually from 9.6 to 6.4 vol (%). Furthermore, the hydorgen and methane decrease from 70 to 45 vol (%) and from 2.2 to 1.7 vol (%), respectively due to the oxidation reactions. As shown in Fig. 7 the HHV increased, from 9.56 to 10.80 MJ.m^{-3}, as the ER

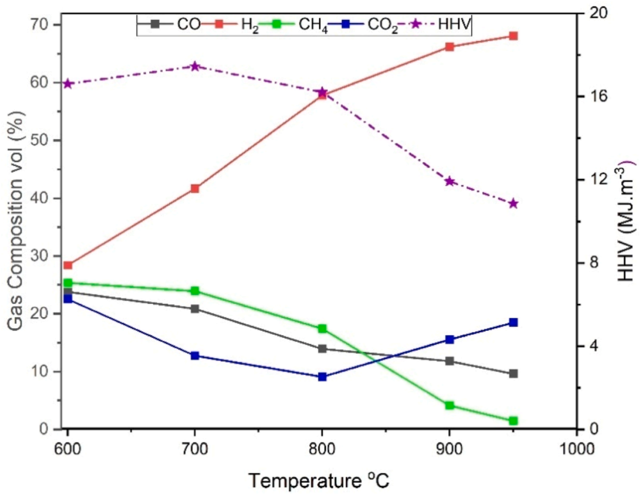

Fig. 6. Effect of temperature on gas composition(vol%) of rice husk, when using steam as gasifying agent.

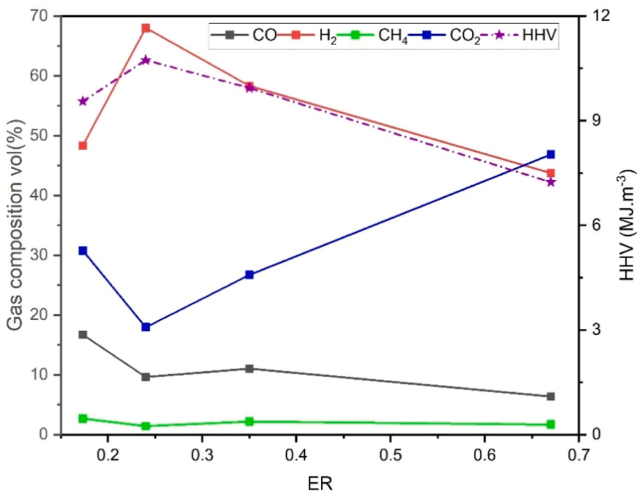

Fig. 7. Effect of Equivalence ratio on gas composition(vol%) of rice husk, when using steam as gasifying agent.

increased from 0.17 to 0.24. However, as the ER rose above 0.24, the HHV began to decline, reaching 7.24 $MJ.m^{-3 \text{ at an ER of } 0.65}$.

3.7. Effect of steam flow rate ratio when using steam as gasifying agent

Fig. 8 shows that the hydrogen content gradually increase as the steam flow rate increases from 0.2 to 0.6 $mL.min^{-1}$. The reason for this is that the addition of steam promotes the transformation and the water-gas shift reactions. However, as the steam flow increases from 0.6 to 0.95 $mL.min^{-1}$, too much steam could cool the reactor temperature, enhancing the oxidation processes for the reaction of hydrogen ($H_2 + 0.5O_2 \leftrightarrow H_2O$), carbon monoxide ($CO + 0.5O_2 \leftrightarrow CO_2$) and Charcoal $C + 0.5O_2 \leftrightarrow CO$. As a result, hydrogen and carbon monoxide are produced less frequently in favor of carbon dioxide. However, carbon monoxide content rises from 9.6 to 16.7 vol (%) with steam flow increasing from 0.6 to 0 .95 $mL.min^{-1}$, indicating hydrocarbon steam reforming reaction. It is imperative to mention that with steam flow rate increasing from 0.2 to 0.6 $mL.min^{-1}$, both carbon monoxide and carbon dioxide content decreases gradually, from 18.7 to 9.6 vol (%) and from 41.3 to 18 vol (%), respectively due to methanation reactions favoring carbon monoxide to react with hydrogen and carbon dioxide to react with hydrogen to produced methane and water vapor, $CO + 3H_2 \leftrightarrow CH_4 + H_2O$ and $CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O$.

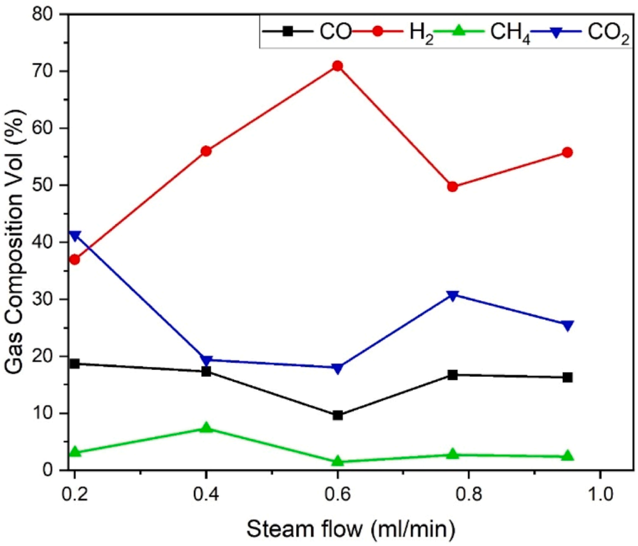

Fig. 8. Effect of steam flow rate on gas composition(vol%) of rice husk.

3.8. Mass balance

The mass balance of the gasification reaction is calculated for the total number of experiments conducted based on elemental analysis. The mass balance for gases and biochar were calculated and balanced with the bio-oil/tar as shown in Table 3. Total mass balance shows that the relative errors are in the range of ±5 %, which is within an acceptable limit.

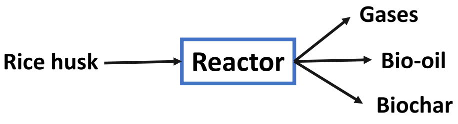

Table 3
Mass balance of gasification tests of rice husk at 950 °C and equivalence ratio 0.24.

Input		Output			Relative error (%)
Components/ elements	Total	Gases	Bio-oil/ Tar	Biochar/ Ash	
Biomass(g)	15	10.67	1.21	2.67	3.0
C (g)	6.22	5.024	Tar	1.17	–
H (g)	0.777	0.465	Tar	0.065	–

Relative error = [(input − output)/input] × 100 %

4. Conclusions

Gasification experiments were performed using rice husk in a lab-scale fixed bed reactor with the aim to produce hydrogen-rich syngas. The rice husk was used due to its high availability in Asian region and was analyzed for its physico-chemical properties. The volatile compounds and carbon content in the rice husk were found to be 58 % and 41 %, respectively. The influence of various parameters such as the physico-chemical properties of the biomass, the temperature of gasification, the size of the particles, the steam flow rate, ER and various gasifying agents such as mixture of (air + steam) and only steam were investigated. The (air + steam) mixture as the gasifying agent, at a constant ER of 0.27 andthe optimum reaction temperature 950 °C, produced a syngas with a high heating value (HHV) of ~7 $MJ.m^{-3}$ and an average syngas composition vol (%) of ~40 % H_2, ~12 % CO, 1.87 % CH_4 and 47.22 % CO_2. In contrast, when only steam was used as the gasifying agent at an ER of 0.24 and a temperature of 950 °C, the produced syngas had a composition vol (%) of ~70 % H_2, ~10 % CO, 1.4 % CH_4 and 18 % CO_2 with an HHV of ~11 $MJ.Nm^{-3}$ (which is comparably higher than the value reported in the literature), showing that steam is a better gasifying agent for the production of hydrogen rich syngas compared to the (air + steam) gasifying mixture. The produced hydrogen rich syngas (with steam) contained significantly high H_2 content (70 %) which indicates that it is highly efficient as fuel precursor. The results show that higher temperatures favor increased hydrogen production, however, excessively high temperatures decrease the HHV of the syngas. Under the optimum condition (ER =0.24, T_g=950 °C), the hydrogen conversion efficiency and energy conversion efficiency were calculated and were found 81 and ~70 %, respectively.

CRediT authorship contribution statement

Ajeet Kumar: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daya Shankar Pandey:** Writing – review & editing, Validation, Supervision. **Tarak Mondal:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scca.2025.100061.

Data availability

Data will be made available on request.

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