Experimental Investigation on The Gasification of High-Ash Indian Coal and Biomass in a Bubbling Fluidized Bed using Air and Steam

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Abstract—**India produces significant amounts of biomass waste, including sugarcane bagasse and sawdust, as well as low-grade, high-ash coal – resources that are not fully tapped into despite their considerable energy potential. Gasification provides a clean and efficient technique for transforming these raw materials into valuable energy sources. This research outlines the design and development of a bubbling fluidized bed gasifier capable of handling high-ash coal (46% ash) and biomass, utilizing air and steam as gasifying agents. Experiments were performed to assess the effects of equivalence ratio (ER), temperature, and steam-to-biomass (S/B) ratio on syngas composition. Raising the temperature from 500°C to 700°C significantly enhanced H_2 and CO production across all feedstocks, indicating improved gasification efficiency at high temperatures. H_2 concentrations increased from 6.7% to 9.1% for sawdust, 10.3–17.5% for bagasse, and 11.4–15.2% for high-ash coal. The optimal ER values for enhancing syngas quality were determined to be 0.35 for biomass and 0.43 for coal. Increasing the S/B ratio from 0.5 to 0.7 significantly increased H_2 content, achieving 25.1% for sawdust and 23.3% for bagasse, attributed to the water-gas shift reaction. The energy balance analysis indicated energy outputs of 12.13 MJ/kg for sawdust, 16.79 MJ/kg for bagasse, and 17.72 MJ/kg for high-ash coal. These results validate the technical feasibility and operational versatility of the gasifier for various feedstocks. The research provides essential insights for optimizing gasification parameters, aiding in cleaner energy production and more efficient use of biomass and coal resources in India.**

Index Terms—**Biomass, Fluidized bed gasifier, Gasification, High ash content coal, Producer gas.**

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I. Introduction

India generates a significant amount of agricultural and forestry waste, with sugarcane bagasse and sawdust being two of the most prevalent types. Sugarcane bagasse, a by-product from sugar production, is produced at around 100 million tonnes each year, accounting for nearly 30% of the total sugarcane processed. While it is extensively used in sugar mills for cogeneration of steam and electricity, boasting an installed cogeneration capacity of about 9,200 MW (Konde et al., 2021), a large portion is still underused or inefficiently utilized, often discarded as waste or low-quality cattle feed. The implementation of second-generation biorefineries in existing sugar mills has been proposed to improve sustainability and enhance the economic value of the excess bagasse (Samsher and Manish, 2022). Likewise, India produces an estimated 8–18 million tonnes of sawdust each year as a by-product from sawmills, plywood production, and furniture manufacturing (Sawdust in India - Availability, Supply Chain, Prices, Surplus - BioBiz, n.d.). Sawdust is mainly utilized for biomass heating, electricity generation, and pellet production, yet a significant amount is still disposed of without fully tapping into its energy potential.

Coal, especially that with high ash content, continues to play a crucial role in India's energy landscape. Nevertheless, its direct combustion is linked to inefficiency and substantial environmental issues stemming from excessive ash production. Gasification offers a contemporary and cleaner method for transforming coal and biomass into valuable energy products. In contrast to traditional combustion, gasification entails the partial oxidation of carbon-based feedstocks (like coal, biomass, or waste) by utilizing a controlled amount of air, oxygen, and/or steam at elevated temperatures and pressures. This technique converts solid feedstocks into syngas – a fuel gas mixture that is abundant in carbon monoxide, hydrogen, methane, and other elements (Maniatis, 1986).

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Gasification presents several unique benefits, such as improved efficiency, the ability to use various fuels, and the capability to generate a variety of valuable products, including electricity, chemicals, and synthetic fuels. These advantages make gasification a potentially effective technology for tackling worldwide energy issues and facilitating the shift toward cleaner, more sustainable energy solutions (Gasifipedia | Netl.Doe.Gov, n.d.). Fig. 1 presents the gasification process and highlights its significance in supporting the energy security.

The gasification step that follows pyrolysis involves chemical reactions among the hydrocarbons in fuel, steam, carbon dioxide, oxygen, and hydrogen in the reactor, as well as chemical reactions among the evolved gases. Of these, char gasification is the most important. When coal is gasified under practical conditions of coal gasification, the following reactions will take place during gasification (Sheikh, 2013).

- **Heterogeneous (solid-gas phase) reactions**
  - **i. Boudard reaction**

    $C_{(s)} + CO_2 \rightarrow 2CO$ ΔH°R= + 172.462 kJ/mole
  - **ii. Water-gas reaction**

    $C_{(s)} + H_2O_{(g)} \rightarrow CO + H_2$ ΔH°R = +131.296 kJ/mole
  - **iii. Direct methanation reaction**

    $C_{(s)} + 2H_2 \rightarrow CH4$ ΔH°R = −74.873 kJ/mole
- Homogeneous (gas phase) reactions
  - **i. Water-gas shift reaction**

    $CO + H_2O_{(g)} \rightarrow CO_2 + H_2$ ΔH°R = −41.166 kJ/mole
  - **ii. Methane shift reaction**

    $CH4 + H_2O_{(g)} \rightarrow CO + 3H_2$ ΔH°R = +206.169 kJ/mole

Among the different types of gasifier configurations, fluidized bed reactors – especially bubbling fluidized beds – have become popular due to their outstanding heat and mass transfer capabilities, flexibility in fuel use, and potential for scalability (Higman and Van der Burgt, 2008). In a bubbling fluidized bed, fine inert particles such as sand or alumina are set in motion by gas streams flowing upwards. When the gas velocity goes beyond the minimum required for fluidization, a dynamic "boiling" effect is reached. This condition guarantees excellent mixing, consistent temperature distribution, and effective interaction between the solid fuel and gasifying agents (Efren Jaimes Figueroa et al., 2014).

The design and improvement of fluidized bed gasifiers, particularly for coal with a high ash content, present significant challenges due to problems like bed agglomeration, defluidization, and ash sintering. This research focuses on the design and creation of a bubbling fluidized bed gasifier specifically engineered to process high ash content coal (46% ash), as well as biomass materials such as sugarcane bagasse and sawdust. Thermodynamic modeling was utilized to forecast the composition of producer gas under optimal operating conditions, which informed the reactor's design and its operating parameters. A comprehensive design methodology can be found in (Priyank, 2024), and the dimensional schematic of the constructed gasifier is illustrated in Fig. 2.

Through the development and experimental validation of a fluidized bed gasifier, this study seeks to address India's underutilization of low-grade coals and copious agricultural leftovers. The study shows a feasible route for effective gasification by examining the impacts of equivalency ratio, steam addition, and operating temperature. The suggested modular system provides a sustainable substitute for open burning of agricultural waste, which raises greenhouse gas emissions and degrades air quality in rural areas. To improve resource utilization and encourage cleaner rural energy practices, the findings support the implementation of decentralized energy solutions that allow farmers to transform biomass into clean syngas for electricity generation via internal combustion engine generators or micro gas turbines.

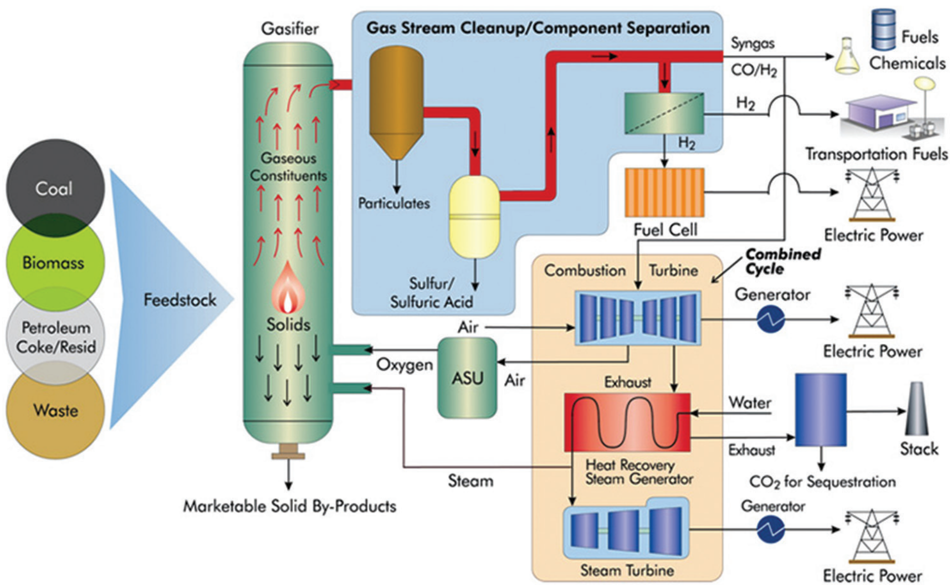

Fig. 1. Gasification process and usefulness (Gasifipedia | *Netl.Doe.Gov*, n.d.).

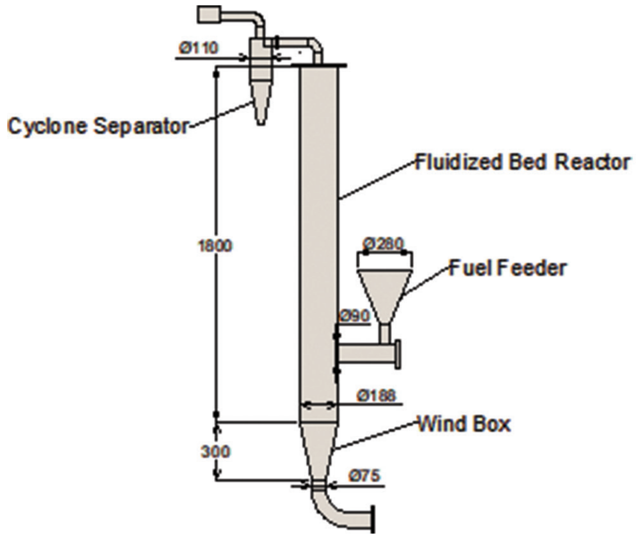

Fig. 2. Dimensional diagram of fluidized bed Gasifier.

II. Materials And Methods

A. Experimental Setup

Fig. 3 shows the fluidized bed gasifier. Trial run was carried out by using three different fuel which are listed below.

Material	Density (%)	Particle diameter
Sawdust	210 kg/m^3±0.02	0.25 mm±0.01
Bagasse	200 kg/m^3±0.02	0.25 mm±0.01
Lignite	800 kg/m^3±0.02	0.25 mm±0.01

The gasifier was initially charged with silica sand, and heating of the sand commenced. On reaching a temperature of 350°C, air was introduced briefly to ensure uniform temperature distribution. Heating continued until the temperature reached 600°C, at which point the feedstock material was introduced into the reactor. Air was then supplied to facilitate combustion, causing a rapid temperature rise to approximately 800°C. Once the temperature stabilized above 800°C, air was continuously fed to maintain fluidization.

Each experimental run was conducted for a duration of 30 min. A reducing gearbox was coupled with the motor to regulate the mass flow rate of the feed material. Airflow was manually adjusted using a flow control valve, with measurements taken at various valve openings – specifically at 10°, 15°, 20°, and 25° – to maintain different equivalence ratios (ER). A total of 25 trial runs were performed to ensure repeatability and reliability of the results.

The producer gas, along with trace amounts of tar and char, passes through a cyclone separator where the char and a portion of the tar are separated. The cleaned producer gas then flows into the burner. To facilitate gas collection, a collector pipe is connected to the burner, and a vacuum pump is used to draw the producer gas into balloons for subsequent gas chromatography analysis. Fig. 4 illustrates the propagated flame observed during the trial run, serving as a validation of the proposed design of the bubbling fluidized bed gasifier.

Experiments are carried out for all three fuels for 30 min once the steady flame propagates with varying ER from 0.3 to 0.4. The ultimate analysis of all fuels is given in Table I. Figs. 5-7 shows the sawdust, bagasse and coal sample.

Fig. 3. Bubbling fluidized bed Gasifier setup.

Fig. 4. Flame propagation.

Fig. 5. Sawdust sample.

TABLE I
Ultimate Analysis

Fuel	C (%)	H (%)	N (%)	S (%)	O (%)	Ash (%)
Sawdust	42.60	5.89	0.40	-	48.59	2.41
Bagasse	49.2	4.69	0.18	-	43	2.91
Coal	49.6	5.69	0.75	0.139	20.58	23.26

B. Validation of the Design

To validate the performance of the developed gasifier, experimental trials were conducted at an ER of 0.28 using

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Fig. 6. Bagasse sample.

Fig. 7. Coal sample.

sugarcane bagasse as the feedstock. The optimal operating condition was achieved with a 20% valve opening. Feedstock was gradually introduced into the reactor once the internal temperature reached 350°C. The blower remained operational until the temperature rose to 800°C, after which the airflow rate was adjusted according to the gasification requirements.

A total of 25 experimental runs were performed to ensure consistency and reliability of the results. Table II presents the experimental data alongside corresponding values from the literature. The close agreement between the experimental and literature data confirms the accuracy of the design methodology and demonstrates that the developed gasifier is well-suited for the intended experimental analysis in this research.

C. Measurement Techniques and Instrumentation Accuracy

To ensure reliable data acquisition during the experimental trials, calibrated instruments with defined accuracy and resolution were employed:

TABLE II
Validation of the Fluidized Bed Gasifier Design

Data type	H_2 (%)	CO (%)	CO_2 (%)
Experimental data	5.2	9.5	13.2
Literature data[6]	4.79	9.68	12.12
% Deviation	8.56	−1.86	8.91

- Temperature measurement: K-type thermocouples were installed at critical locations on the gasifier to monitor temperature. These thermocouples are capable of measuring temperatures up to 1250°C with an accuracy of ±0.75%. Before experimentation, thermocouples were calibrated using a standard reference thermometer to ensure measurement fidelity.
- Air flow rate: A vane-type anemometer was used to measure the air flow rate entering the gasifier. The device has a measurement range of 0.40 m/s to 45 m/s, a resolution of 0.1 m/s, and an accuracy of ± (2% + 1 digit). Calibration was performed using a controlled airflow setup to verify the instrument's response across its operating range.
- Calorific value determination: The calorific value of fuels was determined using a bomb calorimeter with a temperature resolution of 0.01°C. The calorimeter was calibrated using benzoic acid as a standard reference material to ensure accuracy in energy content measurement.
- Producer gas composition: Gas chromatography was employed to analyze the composition of the producer gas. The oven, injector, and detector were operated within a temperature range of ambient to 400°C, with a control accuracy of ±0.1°C. Calibration gases of known composition were used to validate the chromatograph's performance and ensure precise quantification of gas constituents.

All instruments were subjected to routine calibration and error checks before and after the experimental runs to minimize systematic errors and enhance data reliability.

III. Results and Discussion

The effects of key operating parameters on producer gas composition were systematically studied, including the influence of ER, gasification temperature, and steam addition. Experiments were conducted using sawdust, high ash content coal (23.26% ash), and sugarcane bagasse as feedstocks in the newly designed fluidized bed gasifier.

A. Effect of ER on Producer Gas Quality

The ER is widely acknowledged as an essential factor in gasification, having a significant influence on gas composition and reactor performance. An increase in ER typically elevates the temperature of the gasifier due to improved oxidation, whereas lower ER values promote char production and result in a higher unconverted carbon content.

In this research, experiments were conducted using ER values of 0.3, 0.35, and 0.4 for sawdust and bagasse, and 0.35, 0.4, and 0.43 for high ash coal. Airflow was meticulously managed using a flow control valve and measured with an anemometer, while the rate of fuel feeding remained constant.

For sawdust, as the ER increased from 0.3 to 0.35, concentrations of both H_2 and CO increased (refer to Table III), peaking at an ER of 0.35. A further increase to 0.4 resulted in a decline, which was attributed to heightened oxidation processes converting CO and H_2 into CO_2 and H_2O.

This behavior is also illustrated in Figs. 8-10, which shows an optimal ER for maximizing combustible gas components.

Coal with high ash content: For coal, raising the ER from 0.35 to 0.43 steadily enhanced the concentrations of H_2 and CO (refer to Table IV). The experimental findings were also evaluated against predictions made by a two-phase equilibrium model, showing strong alignment with a deviation of <5%.

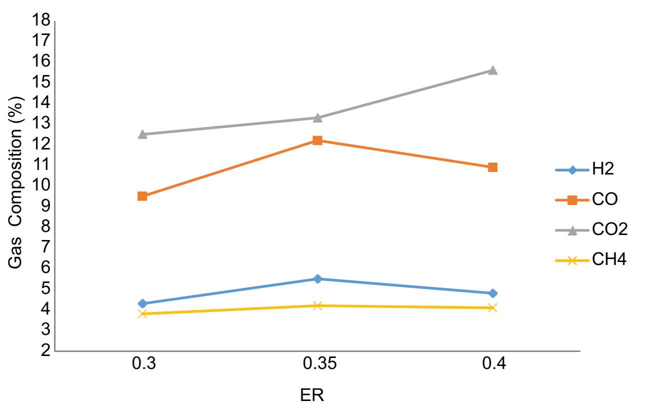

Fig. 8. Equivalence ratio versus producer gas composition for saw dust.

TABLE III
EFFECT OF EQUIVALENCE RATIO OF PRODUCER GAS COMPOSITION FOR SAWDUST

Equivalence ration	H_2 (%)	CO (%)	CH_4 (%)	CO_2 (%)
0.3	4.3	9.5	3.8	12.5
0.35	5.5	12.2	4.2	13.3
0.4	4.8	10.9	4.1	15.6

Sugarcane bagasse: Like sawdust, the concentrations of H_2 and CO rose from ER 0.3 to 0.35, then decreased at 0.4 (Table V).

These trends indicate that the ER has a non-linear impact, with a moderate ER yielding the best quality of syngas. The findings are in agreement with existing literature, like that of (Aranda et al., 2016), (Karatas, Olgun and Akgun, 2013) and (Gupta and De, 2022), which show comparable gas composition trends for various ER values.

B. Effect of Temperature on Producer Gas Quality

Additional experiments were carried out to investigate how reactor temperature affects gas composition while maintaining fixed ER values (0.35 for sawdust and bagasse; 0.4 for coal). Gas samples were gathered at temperatures of 500°C, 600°C, and 700°C, and were analyzed through gas chromatography.

As indicated in Table VI, increasing the temperature led to elevated concentrations of H_2 and CO, accompanied by a decrease in CO_2 levels. This observation can be explained by enhanced reaction kinetics, the greater influence of the Boudouard and water-gas shift reactions, along with secondary cracking reactions occurring at higher temperatures. However, continuous decrease in CO_2 observed due to equilibrium shift of water-gas shift reaction toward the reactant direction (Pandey, Srivastava and Kumar, 2022).

Further experiments were performed to investigate how reactor temperature affects the results. Figs. 11-13 illustrate the graphical variations, emphasizing the positive effects of increased temperatures on syngas quality. The trends observed align with those described by (Vajpeyi et al., 1986) and (Jayaraman and Gokalp, 2015) and reinforce the optimized temperature ranges for each type of feedstock.

C. Effect of Steam Addition on Producer Gas Quality

To investigate the impact of steam addition, experiments were carried out at a gasification temperature of 700°C with different steam-to-biomass (S/B) ratios (0.5, 0.6, and 0.7). Steam was produced at 100°C and directly fed into the gasifier.

Increasing the S/B ratio improved the generation of H_2 through steam gasification reactions and the water-gas

TABLE IV
EFFECT OF EQUIVALENCE RATIO OF PRODUCER GAS COMPOSITION FOR HIGH ASH COAL (23.26%)

Equivalence ration	Experimental H_2	Predicted H_2	Experimental CO	Predicted CO	Experimental CH_4	Predicted CH_4
0.35	11	13.3	10	12.3	0.7	0.55
0.4	13	15.9	15	18.2	1.2	0.91
0.43	15	18.1	20	23.3	2.5	2.1

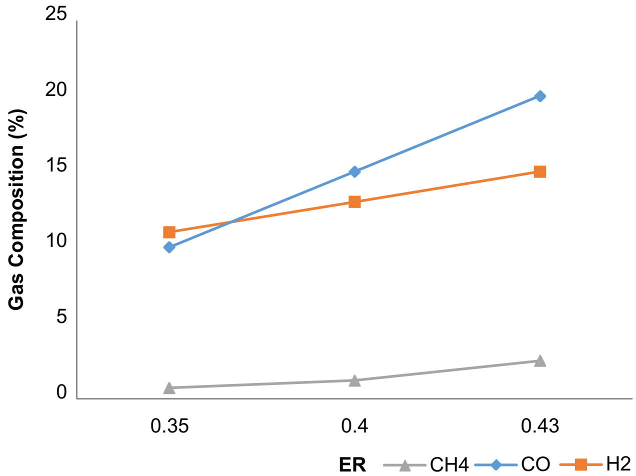

Fig. 9. Equivalence ratio versus producer gas composition for high ash coal.

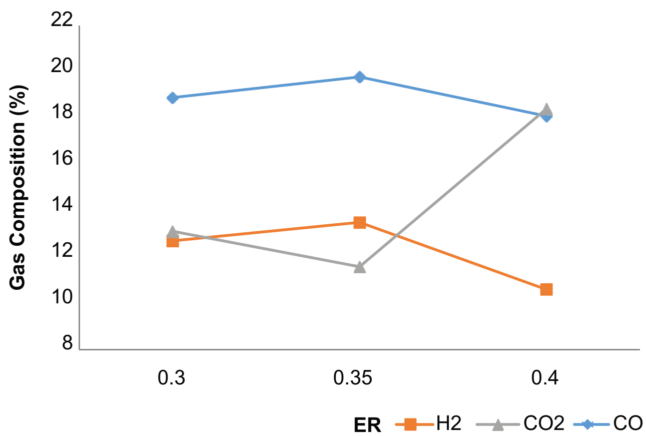

Fig. 10. Equivalence ratio versus producer gas composition for bagasse.

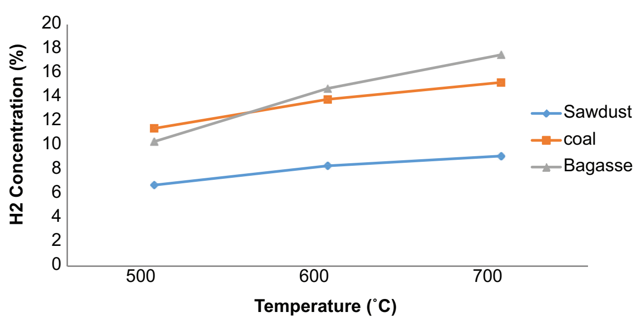

Fig. 11. Temperature versus H_2 concentration for sawdust, bagasse and coal.

shift reaction, while the concentration of CO decreased (Tables VII and VIII). A slight increase in CO_2 levels was also noted, indicating higher CO conversion.

As shown in Figs. 14 and 15, increased S/B ratios consistently promoted hydrogen enrichment in the producer gas. These findings support the conclusions reached by (Yang et al., 2015; Yang, Zhang and Peng, 2016), (Chavan et al., 2012) and (Vajpeyi et al., 1986), verifying that the addition of steam can enhance gas quality and calorific value.

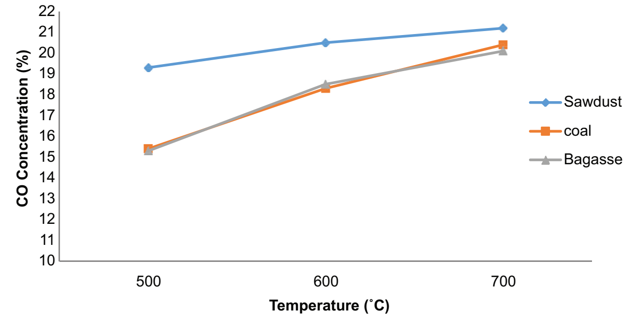

Fig. 12. Temperature versus CO concentration for sawdust, bagasse and coal.

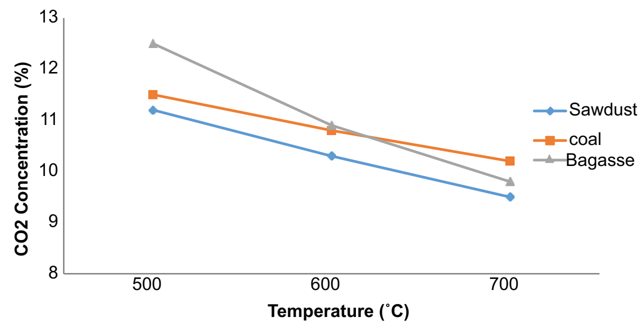

Fig. 13. Temperature versus CO_2 Concentration for sawdust, bagasse and coal.

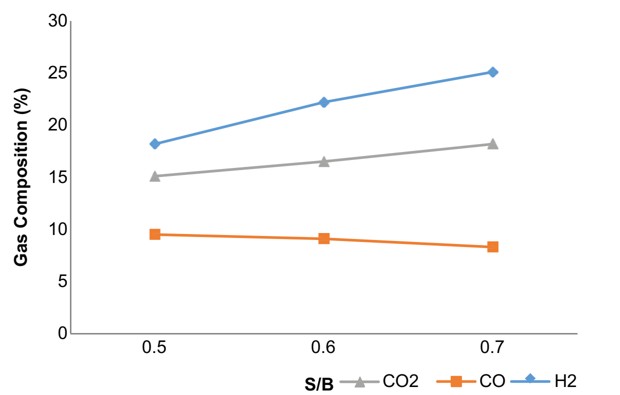

Fig. 14. Steam-to-biomass versus producer gas composition for sawdust.

TABLE V
EFFECT OF EQUIVALENCE RATIO OF PRODUCER GAS COMPOSITION FOR SUGARCANE BAGASSE

Equivalence ratio	H_2 (%)	CO (%)	CO_2 (%)
0.3	12.7	18.9	13.11
0.35	13.5	19.8	11.58
0.4	10.6	18.1	18.41

TABLE VI
Effect of Temperature on Producer Gas Composition for saw Dust, Bagasse and High Ash Content Coal

Temperature (°C)	Sawdust			Coal			Bagasse		
	H_2 (%)	CO (%)	CO_2 (%)	H_2 (%)	CO (%)	CO_2 (%)	H_2 (%)	CO (%)	CO_2 (%)
500	6.7	19.3	11.2	11.4	15.4	11.5	10.3	15.3	12.5
600	8.3	20.5	10.3	13.8	18.3	10.8	14.7	18.5	10.9
700	9.1	21.2	9.5	15.2	20.4	10.2	17.5	20.1	9.8

TABLE VII
Effect of Steam to Biomass Ratio on Producer Gas Composition for Sawdust

S/B	H_2	CO	CO_2
0.5	18.2	9.5	15.1
0.6	22.2	9.1	16.5
0.7	25.1	8.3	18.2

TABLE VIII
Effect of Steam to Biomass Ratio on Producer Gas Composition for Sugarcane Bagasse

S/B	H_2 (%)	CO (%)	CO_2 (%)
0.5	14.3	14.8	13.2
0.6	19.2	13.2	14.1
0.7	23.3	11.3	15.2

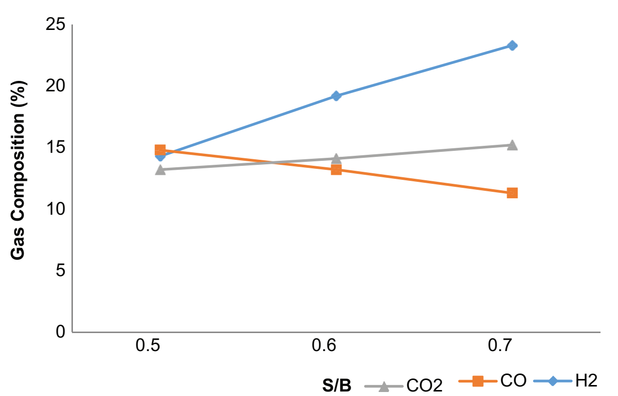

Fig. 15. Steam-to-biomass versus producer gas composition for sugarcane bagasse.

IV. Conclusion

The current investigation illustrates the design, construction, and experimental assessment of a bubbling fluidized bed gasifier utilizing sawdust, sugarcane bagasse, and coal with high ash content as feed materials, employing air and steam as gasifying agents. A systematic examination was conducted on the impact of critical operating parameters – specifically temperature, ER, and S/B ratio – on the composition of producer gas. The primary conclusions drawn from this study are summarized below:

A. Effect of Temperature

Raising the gasification temperature from 500°C to 700°C significantly improved the yields of hydrogen and carbon monoxide for all feedstocks. In the case of sawdust, the concentration of H_2 grew from 6.7% to 9.1%, and CO increased from 19.3% to 21.2%. Likewise, for sugarcane bagasse, H_2 escalated from 10.3% to 17.5% and CO from 15.3% to 20.1%; for high ash coal, H_2 climbed from 11.4% to 15.2%, while CO rose from 15.4% to 20.4%. This observed effect is linked to the enhancement of endothermic reactions, such as the Boudouard and water-gas shift reactions, that occur at higher temperatures.

B. Effect of ER

The ER was determined to play a key role in the quality of syngas. For both sawdust and bagasse, the concentrations of H_2 and CO saw an increase with ER values up to 0.35, beyond which they declined due to excessive oxidation. In the case of high ash coal, H_2 and CO continued to rise until an ER of 0.43, with H_2 increasing from 11% to 15% and CO from 10% to 20%. This supports the notion that there is an optimal ER range for each type of feedstock that maximizes the yield of combustible gases while reducing CO_2 emissions.

C. Effect of Steam Addition

Raising the S/B ratio from 0.5 to 0.7 resulted in a significant increase in the hydrogen content of the producer gas. In the case of sawdust, the H_2 concentration rose from 18.2% to 25.1%, along with an increase in CO_2 from 15.1% to 18.2% and a decrease in CO from 9.5% to 8.3%. Comparable patterns were noted for sugarcane bagasse, where H_2 climbed from 14.3% to 23.3% and CO fell from 14.8% to 11.3%. These findings underscore the improved activity of the water-gas shift reaction, which promotes hydrogen generation and enhances the overall calorific value of the gas.

The study validates the fluidized bed gasifier's operational adaptability and technological viability for processing a range of feedstocks, including coal and other materials with a high ash concentration. Significant insights for enhancing syngas composition are provided by the thorough parametric analysis, which is crucial for developing cleaner and more effective energy production systems. The energy potential and usefulness of the developed gasification system were further supported by the energy balance study, which showed total energy outputs of 12.13 MJ/kg for sawdust, 16.79 MJ/kg for sugarcane bagasse, and 17.72 MJ/kg for high ash coal.

By facilitating the efficient use of low-grade coal and agricultural waste, this study offers a scalable answer for India's rural energy needs in addition to its technical contributions. The modular gasifier design gives farmers a cleaner option to open biomass burning by supporting localized power generation using internal combustion engine generators or micro gas turbines. This study makes a significant contribution to resource optimization and environmental preservation in agro-industrial areas by encouraging sustainable energy conversion and lowering greenhouse gas emissions.

V. Data Available with the Paper or Supplementary Information

The authors declare that the data supporting the findings of this study are available within the paper.

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