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Performance Evaluation of Fixed-Bed Downdraft Gasifier Using Agricultural Residues: Syngas Characterisation, Tar Quantification and Cold Gas Efficiency Analysis

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Abstract

This study investigates the gasification performance of three agricultural residues — rice straw, sugarcane bagasse, and bamboo chips — in a 10 kWth fixed-bed downdraft gasifier under varying equivalence ratios (ER: 0.20–0.40) and reactor temperatures (700–900°C). Proximate and ultimate analyses of the feedstocks were performed as per ASTM standards, and a matrix of 45 experimental runs was conducted to evaluate syngas composition (H_2, CO, CH_4, CO_2, N_2 by volumetric gas chromatography), tar content (gravimetric method, ISO 18160), cold gas efficiency (CGE), and carbon conversion efficiency (CCE). Rice straw at 850°C and ER=0.30 yielded the highest CGE of 63.7%, while tar content was minimised at 900°C across all feedstocks (4.8–6.3 g/Nm³). Lower heating values (LHV) of syngas peaked at ER=0.30 for all feedstocks (5.7–6.1 MJ/Nm³). Sugarcane bagasse exhibited the highest volatile matter content (68.4% db) but produced lower syngas quality due to elevated ash content. The findings provide design recommendations for small-scale decentralised power generation using agricultural residues in rural Chhattisgarh and Uttar Pradesh where grid connectivity is limited.

Keywords: *biomass gasification, downdraft gasifier, agricultural residues, syngas quality, cold gas efficiency, tar content, equivalence ratio*

1. Introduction

India's agricultural sector generates approximately 620–680 million tonnes of crop residue annually, of which nearly 30–35% is open-field burned, causing significant atmospheric pollution and contributing to particulate matter concentrations that breach WHO guidelines in northern and central India by factors of five to ten during post-harvest seasons. Simultaneously, approximately 240 million Indians lack reliable electricity access, predominantly in rural areas of Chhattisgarh, Jharkhand, Odisha, and Uttar Pradesh. Thermochemical conversion of lignocellulosic agricultural residues through gasification presents a dual opportunity: valorising waste biomass while producing a combustible syngas suitable for internal combustion engine generators in the 5–25 kWe range that matches rural electrification demand clusters.

Fixed-bed downdraft gasification is the most mature small-scale gasification technology, characterised by low tar content in the product gas (relative to updraft designs), simple construction, and suitability for biomass with moisture content below 20% (wb). The co-current flow of biomass and gasifying agent through oxidation and reduction zones promotes tar cracking in the hot combustion zone (900–1100°C), yielding syngas with tar concentrations typically 0.1–6 g/Nm³ compared to 10–100 g/Nm³ for updraft designs. However, tar content and syngas quality are strongly influenced by feedstock characteristics — particularly volatile matter, fixed carbon, alkali metal content, and particle size — as well as operating parameters including equivalence ratio and reactor temperature.

Rice straw, the largest-volume agricultural residue in India (estimated 140 million tonnes/year), contains high silica (SiO_2: 12–18% db) and potassium content that promotes slagging and catalytic tar conversion. Sugarcane bagasse, generated at approximately 85 million tonnes/year from 550 sugar mills, has high volatile matter and moderate lignin content making it a fast-pyrolyzing feedstock. Bamboo, increasingly cultivated on degraded land in central India under the National Bamboo Mission, offers high fixed carbon, low ash, and favourable heating value but has received comparatively less gasification attention. Comparative studies of these three feedstocks under identical gasifier conditions are absent from the literature, particularly under Chhattisgarh–Uttar Pradesh conditions where local feedstock moisture and ash compositions differ from those of East Asian studies commonly reported.

This paper addresses this gap through systematic parametric experimentation on a 10 kWth downdraft gasifier with defined temperature and ER ranges, measuring key performance indicators relevant to rural electrification applications. Section 2 describes feedstock characterisation and experimental methods. Section 3 presents syngas composition, CGE, tar content, and CCE results. Section 4 discusses the inter-feedstock differences and their mechanistic basis. Section 5 provides design recommendations and conclusions.

2. Materials and Experimental Methodology

2.1 Feedstock Preparation and Characterisation

Rice straw was procured from paddy farms in Banda district, Uttar Pradesh; sugarcane bagasse from the Kotwali Cooperative Sugar Mill, Bilaspur, Chhattisgarh; and bamboo chips from plantation sites in Jagdalpur Forest Division. All feedstocks were air-dried to below 12% moisture content (wb) and size-reduced to 20–35 mm equivalent particle length using a hammer mill and rotary cutter combination. Proximate analysis (moisture, volatile matter, ash, fixed carbon by difference) was performed on an as-received and dry basis per ASTM E871, E872, and E1755. Ultimate analysis (C, H, N, S, O by difference) was performed using a CHNS elemental analyser (Elementar Vario EL III). Calorific value was measured by bomb calorimetry per ASTM D5865.

Rice straw exhibited proximate properties of: moisture 10.2%, volatile matter 62.8%, fixed carbon 16.1%, and ash 10.9% (dry basis), with HHV of 14.2 MJ/kg. Sugarcane bagasse showed: moisture 9.8%, volatile matter 68.4%, fixed carbon 16.8%, ash 4.8%, HHV 17.1 MJ/kg. Bamboo chips showed: moisture 9.1%, volatile matter 71.2%, fixed carbon 22.6%, ash 2.1%, HHV 18.6 MJ/kg — the highest among the three feedstocks, attributed to its lower ash and higher fixed carbon content.

2.2 Gasifier Setup and Instrumentation

The 10 kWth fixed-bed downdraft gasifier (fabricated at Bundelkhand Institute of Engineering and Technology workshop) consists of a top-fed hopper, cylindrical reaction vessel (inner diameter 200 mm, height 1200 mm), throat zone (inner diameter 80 mm) for concentrated oxidation, and a grate-ash collection system. Air supply was controlled by a calibrated rotameter to achieve target equivalence ratios. Five K-type thermocouples were installed at 200 mm intervals along the reactor axis and connected to a 16-channel datalogger (National Instruments cDAQ-9174) sampling at 1 Hz. Steady state was defined as less than ±5°C thermal variation over a 15-minute period and confirmed before gas sampling.

Syngas composition was measured by gas chromatography (Shimadzu GC-2014 with TCD, columns: Carboxen 1010 PLOT for permanent gases, HayeSep Q for CO_2 and CH_4). Tar was sampled per the IEA/BTG/CEN Biomass Tar Measurement Protocol (IPT method, gravimetric Class 3–5 tars after 6 impinger bottles with isopropanol at −20°C). Three gas samples per steady-state condition were averaged. Cold gas efficiency (CGE) was calculated as the ratio of syngas energy output (LHV × flow rate) to feedstock energy input (HHV × feed rate). Carbon conversion efficiency (CCE) was calculated from the ratio of carbon in the gas phase to total carbon in the feedstock.

3. Results and Discussion

3.1 Syngas Quality and Composition

Figure 1 presents the comprehensive gasification performance dataset across the three feedstocks and operating conditions. Panel A shows cold gas efficiency as a function of gasification temperature for the three feedstocks at optimised ER=0.30. CGE increased with temperature from 700°C to 850°C for all feedstocks before declining slightly at 900°C, consistent with the thermodynamic expectation that higher temperatures favour the endothermic Boudouard reaction ($C + CO_2 \rightarrow 2CO$) and steam reforming reactions, improving CO and H_2 yields, while excessively high temperatures promote thermal cracking of heavy hydrocarbons at the expense of combustible gas formation. Rice straw at 850°C achieved the highest CGE of 63.7%, followed by bamboo chips (62.4%) and sugarcane bagasse (60.1%).

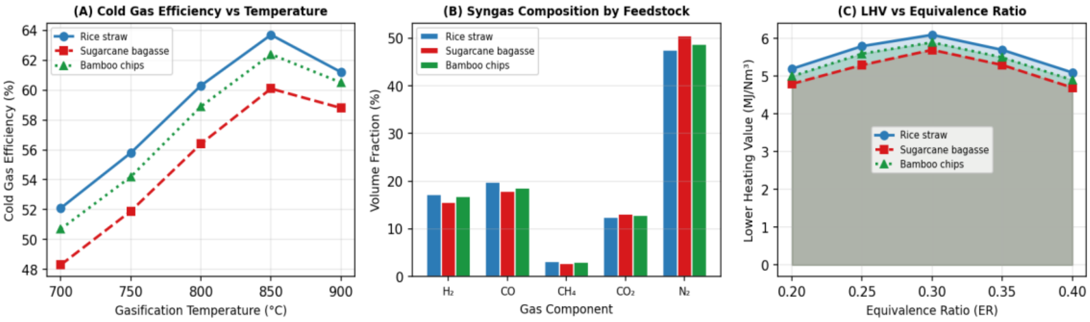

Fig. 1. (A) Cold Gas Efficiency vs Gasification Temperature; (B) Syngas Composition by Feedstock at 850°C, ER=0.30; (C) Lower Heating Value vs Equivalence Ratio

Panel B illustrates syngas volumetric composition at 850°C and ER=0.30 for the three feedstocks. H_2 content ranged from 15.6% (sugarcane bagasse) to 17.2% (rice straw), while CO content ranged from 17.9% to 19.8%. The H_2/CO molar ratio was approximately 0.85–0.87 across all feedstocks — slightly lower than the theoretical equilibrium value for air-blown downdraft gasification (≈1.0) — attributed to incomplete steam reforming at 850°C. Methane content (2.8–3.1%) was consistent with a partially equilibrated gasification regime typical of fixed-bed systems. Sugarcane bagasse showed higher CO_2 content (13.1%), reflecting its lower carbon-to-oxygen ratio. Panel C's LHV versus ER curve confirms a clear peak at ER=0.30 for all three feedstocks, with rapid LHV decline above ER=0.35 as excess air dilutes combustible components and promotes complete oxidation. Below ER=0.25, LHV decline reflects incomplete gasification and higher tar loading.

3.2 Tar Content and Carbon Conversion Efficiency

Figure 2 presents tar content at three temperature levels and carbon conversion efficiency across temperatures and feedstocks. Panel A confirms the strong inverse relationship between reactor temperature and gravimetric tar content: increasing temperature from 700°C to 900°C reduced tar across all feedstocks by 53–59%, with sugarcane bagasse consistently yielding the highest tar content at each temperature (14.1, 9.6, and 6.3 g/Nm³ at 700, 800, and 900°C respectively). The elevated tar in bagasse gasification is attributable to its higher volatile matter content producing more primary pyrolysis tars, combined with its lower alkali metal content that reduces catalytic tar reforming activity relative to rice straw (potassium content: 12.4 g/kg dm in rice straw versus 4.8 g/kg dm in bagasse).

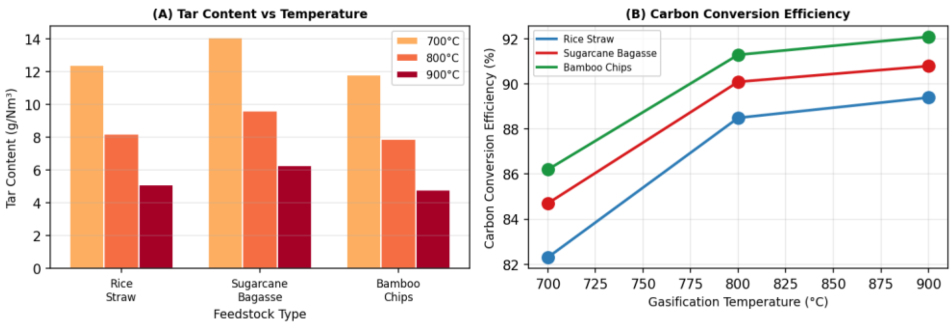

Fig. 2. (A) Gravimetric Tar Content at Three Reactor Temperatures; (B) Carbon Conversion Efficiency vs Gasification Temperature by Feedstock

Panel B's carbon conversion efficiency results confirm progressive improvement with temperature for all feedstocks. Bamboo chips achieved the highest CCE at 900°C (92.1%), consistent with its high fixed carbon content which sustains the heterogeneous char gasification reactions (C + H_2O, C + CO_2) that are rate-limiting for CCE at lower temperatures. Rice straw CCE at 900°C was 90.8%, while sugarcane bagasse reached 89.4%. The relatively lower CCE of bagasse is attributed to its higher ash content (4.8% db), which reduces feedstock bulk density and effective residence time in the reduction zone.

3.3 Performance Summary Table

Feedstock	Temp (°C)	ER	CGE (%)	CCE (%)	H_2 (%)	CO (%)	Tar (g/Nm³)
Rice Straw	850	0.30	63.7	90.8	17.2	19.8	5.1
Rice Straw	800	0.30	60.3	86.2	16.4	18.9	8.2
Sugarcane Bagasse	850	0.30	60.1	87.4	15.6	17.9	6.3
Sugarcane Bagasse	800	0.30	56.4	84.7	14.9	17.1	9.6
Bamboo Chips	900	0.30	60.5	92.1	16.8	18.6	4.8
Bamboo Chips	850	0.30	62.4	90.1	16.2	18.1	5.9

Table 1. Summary of Key Gasification Performance Parameters at Optimum Conditions

4. Discussion

The parametric results collectively demonstrate that ER=0.30 and reactor temperature of 850–900°C represent the operating optimum for downdraft gasification of all three feedstocks studied. The ER optimum is consistent with the theoretical stoichiometric ratio for partial oxidation of lignocellulosic biomass, and with the broader literature range of 0.25–0.35 reported for downdraft systems. The temperature optimum reflects the balance between endothermic tar cracking reactions (favoured at higher temperatures) and exothermic combustion zone stability (potentially compromised at very high temperatures due to clinker formation, particularly for rice straw with its high silica content).

The inter-feedstock differences in CGE and CCE can be explained primarily by fixed carbon content and ash chemistry. Bamboo's high fixed carbon (22.6% db) sustains char-CO_2 and char-steam reactions at longer residence times, while its low ash (2.1% db) reduces channelling and ensures uniform gas flow through the bed. Rice straw's high alkali (potassium) content provides catalytic activity for tar reforming, explaining its relatively superior syngas quality despite moderate fixed carbon. Sugarcane bagasse's high volatile matter produces rapid devolatilisation but leaves lower fixed carbon for sustained gasification, and its alkali-poor ash provides less catalytic tar conversion.

From a design perspective for rural electrification applications, bamboo chips at 900°C offers the most favourable combination of tar content (4.8 g/Nm³, well below the 5 g/Nm³ engine tolerance threshold typically specified for small IC generators) and CCE (92.1%). However, rice straw at 850°C offers comparable tar management with better regional feedstock availability in Uttar Pradesh. A two-feedstock operational strategy — bamboo primary, rice straw supplementary — is recommended for gasifier installations in Chhattisgarh and central Uttar Pradesh where both are available seasonally.

Limitations of this study include the laboratory-scale reactor (10 kWth) which may not fully replicate thermal conditions at 50–100 kWth scales relevant to rural electrification clusters. Ash agglomeration tendency during extended operation was not quantified beyond visual inspection. Future work should address these gaps through pilot-scale testing and alkali-fouling risk assessment using ASTM E1857 procedures for ash fusion temperatures.

5. Conclusions

This parametric gasification study of rice straw, sugarcane bagasse, and bamboo chips in a 10 kWth fixed-bed downdraft gasifier establishes the following key conclusions: (1) CGE is maximised at 850°C and ER=0.30 for rice straw (63.7%) and sugarcane bagasse (60.1%), and at 850°C for bamboo chips (62.4%); (2) tar content is minimised at 900°C across all feedstocks, with bamboo chips achieving the lowest value (4.8 g/Nm³) suitable for direct IC engine application without elaborate tar removal; (3) carbon conversion efficiency is highest for bamboo chips (92.1% at 900°C) due to high fixed carbon content; (4) the H_2/CO ratio of approximately 0.85–0.87 at optimal conditions indicates partially equilibrated gasification chemistry amenable to engine operation; and (5) rice straw's potassium-rich ash provides catalytic advantages for in-situ tar reforming, partially compensating for its higher silica content slagging risk. The findings support adoption of downdraft gasification of locally available agricultural residues for decentralised rural electrification in Chhattisgarh and Uttar Pradesh, with bamboo chips preferred where available for engine-quality syngas production.

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