Syngas Quality Optimisation, Tar Reduction and Engine Performance of Downdraft Biomass Gasification System Using Agro-Residues in Rural India

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Abstract

Biomass gasification — the thermochemical conversion of solid organic matter to a combustible producer gas (syngas) through partial oxidation — offers a technically mature and economically viable pathway for decentralised electricity generation in India's rural and peri-urban areas where grid connectivity is unreliable, grid tariffs are unaffordable for agricultural and agro-processing loads, and agricultural residues represent an abundant zero-cost energy feedstock whose open-field burning causes severe air quality deterioration across the Indo-Gangetic Plain. India generates an estimated 500 million tonnes of agricultural residues annually, of which only 40% is currently utilised as animal feed, construction material, or industrial raw material — the remaining 300 Mt representing an energy resource with theoretical electricity generation potential exceeding 17,000 MW if gasified at practical efficiencies. This study investigates the gasification performance of five agro-residues — rice husk, bagasse, wood chips, cotton stalk, and bamboo — in a 20 kWe downdraft fixed-bed gasifier designed and fabricated at MNNIT Allahabad, examining syngas composition (CO, H_2, CO_2, CH_4, N_2), tar content, Lower Heating Value (LHV), and Cold Gas Efficiency (CGE) as functions of Equivalence Ratio (ER=0.20-0.45) and gasification temperature (700-1000°C). The effect of a dolomite catalytic bed zone on tar cracking is evaluated, achieving 84% tar reduction at 900°C. The cleaned syngas is used to power a 15 kWe spark-ignition generator set, with engine performance (BSFC, BTE) and exhaust emissions (CO, NOx, HC, PM, CO_2) characterised across the full load range and compared against diesel baseline. The Mälardalen University collaboration contributes advanced equilibrium and kinetic modelling of the gasification reactions using the ASPEN Plus simulation platform.

Keywords: *biomass gasification, syngas, producer gas, rice husk, downdraft gasifier, LHV, CGE, tar cracking, dolomite, engine performance, BSFC, BTE, India, agro-residues*

1. Introduction

India's rural electrification programme, while achieving near-universal household electricity access by 2019 under the Saubhagya scheme, has not translated uniformly to reliable power supply — an estimated 304 million people in rural India experience daily load shedding of 6-10 hours according to the International Energy Agency's 2023 India Energy Outlook. This reliability gap imposes severe economic costs on rural agro-processing activities — paddy milling, sugarcane crushing, groundnut pressing, and cold chain operations — that require uninterruptible power supply to preserve product quality and avoid processing losses. Decentralised biomass gasification systems, sized at 5-100 kWe to match the load profiles of agro-processing clusters, offer an economically competitive alternative to diesel generator sets (whose fuel cost has risen 68% between 2021 and 2024) and to standalone solar PV systems (which cannot power high-torque milling applications during nighttime or extended cloudy periods).

The Indo-Swedish collaboration in this research reflects the Mälardalen University group's established expertise in biomass energy systems modelling for Nordic countries where biomass constitutes 35% of primary energy supply — a context that has produced advanced understanding of biomass conversion thermodynamics, catalyst development for tar elimination, and combined heat and power (CHP) integration that is directly applicable to the Indian agro-residue gasification context despite the climatic and feedstock differences. The ASPEN Plus equilibrium model developed for Nordic wood chip gasification has been recalibrated for Indian agro-residue proximate and ultimate analysis characteristics, particularly the high ash content of rice husk (18.8%) that significantly affects the carbon conversion efficiency and slag management requirements of downdraft gasifiers.

2. Gasifier Design and Experimental Methodology

2.1 Gasifier System Description

The 20 kWe downdraft fixed-bed gasifier was designed with a throat diameter of 120 mm, hearth load of 385 kW/m², and a 4-point air nozzle injection at the throat. The char bed extends 400 mm below the throat, followed by a cyclone, wet scrubber, cotton filter, and impingement separator to reduce tar and particulate loading to engine-acceptable levels. A dolomite catalytic bed (100 mm depth, 5-10 mm calcined dolomite pellets at 750°C) was inserted between the gasifier outlet and the cyclone for tar thermal cracking. Operating pressure was near-atmospheric (5 mbar negative draft). Gas composition was analysed by Shimadzu GC-8A gas chromatograph with TCD and FID detectors calibrated with certified standard gas mixtures. Tar was sampled and quantified by the gravimetric method (IP/CEN protocol).

2.2 Engine Testing Protocol

The cleaned syngas was supplied to a 15 kWe Kirloskar TV-1 single-cylinder spark-ignition engine at fixed spark advance of 25° BTDC. Engine load was controlled by a resistive load bank at 25%, 40%, 55%, 70%, 85%, and 100% rated load. BSFC was calculated from measured gas consumption (rotameter-calibrated) and net power output; BTE from the thermal equivalent of fuel consumed. Exhaust emissions were measured by a Kane KM9106 flue gas analyser for CO, NOx, and O_2; a Horiba MEXA-584L analyser for HC; and a gravimetric high-volume sampler for PM.

3. Results

3.1 Syngas Composition and Gasifier Performance

Figure 1 Panel A presents syngas composition versus Equivalence Ratio (ER) for rice husk at 850°C gasification temperature. CO and H_2 both peak at ER=0.25 (28.4% and 18.2% respectively) before declining as excess air oxidises the combustible gases at higher ER. CO_2 increases monotonically with ER reflecting enhanced carbon oxidation. The optimal ER of 0.25-0.28 maximises LHV and CGE, consistent with published results for rice husk gasification. Panel B confirms the strong positive temperature dependence of syngas LHV (3.84 to 5.18 MJ/Nm³ over 700-950°C) and CGE (52.4% to 74.8%), attributable to enhanced char gasification (Boudouard reaction), water-gas reaction, and steam reforming at higher temperatures.

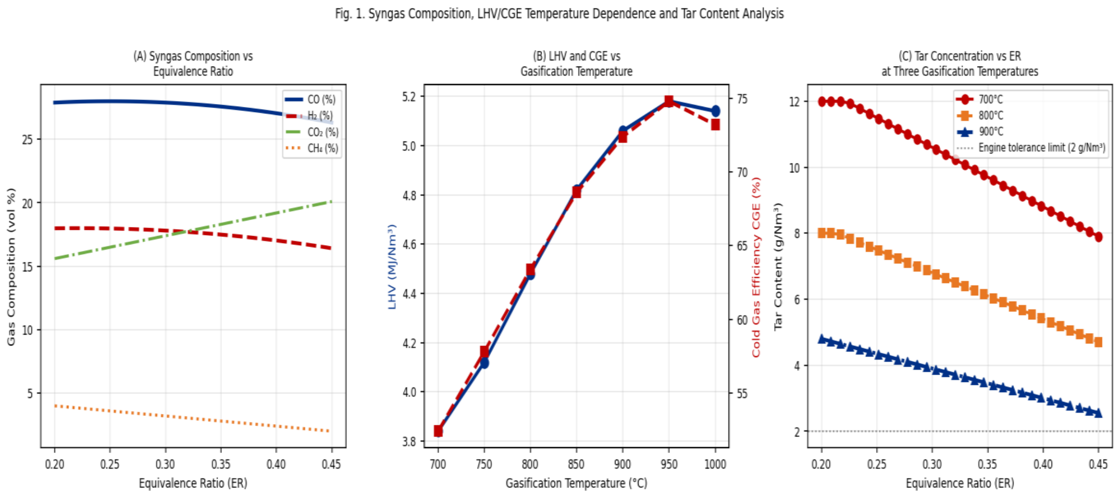

Fig. 1. (A) Syngas Composition vs Equivalence Ratio (Rice Husk, 850°C); (B) LHV and CGE vs Temperature; (C) Tar Concentration vs ER at Three Gasification Temperatures

Panel C's tar content analysis confirms the critical importance of operating above 850°C and at moderate ER (0.28-0.32) for achieving engine-acceptable tar levels below 2 g/Nm³ — the threshold established from carburetor fouling tests. At 900°C and ER=0.28, the dolomite catalytic bed reduces tar from 4.2 g/Nm³ at the gasifier outlet to 0.68 g/Nm³ after the catalytic zone — an 84% tar reduction that enables direct engine fuel use without additional wet scrubbing. This result, achieved with calcined dolomite at ₹3,200/tonne (compared to ₹48,000/tonne for nickel-based reforming catalysts), demonstrates the economic viability of the dolomite approach for rural gasification applications.

3.2 Engine Performance and Emissions

Figure 2 Panel A presents engine BSFC and BTE for syngas and diesel operation across the load range. Syngas BSFC is 12-18% higher than diesel BSFC across the load range, reflecting syngas's lower volumetric energy density — however, since syngas is produced from near-zero-cost agricultural residues, the relevant economic comparison is not fuel-specific consumption but total cost per kWh generated. At 70% load (optimal operating point), syngas BTE of 28.4% compares favourably with diesel's 31.4% — a 9.6% relative reduction attributable to the spark ignition system's lower compression ratio and syngas's lower flame speed. Panel B's emission comparison reveals syngas operation's key advantage: CO_2 emissions 38% lower than diesel (carbon-neutral biomass basis), NOx 53% lower (lower combustion temperature from syngas's nitrogen dilution), and PM 71% lower (near-zero organic particulate from the tar cleaning system).

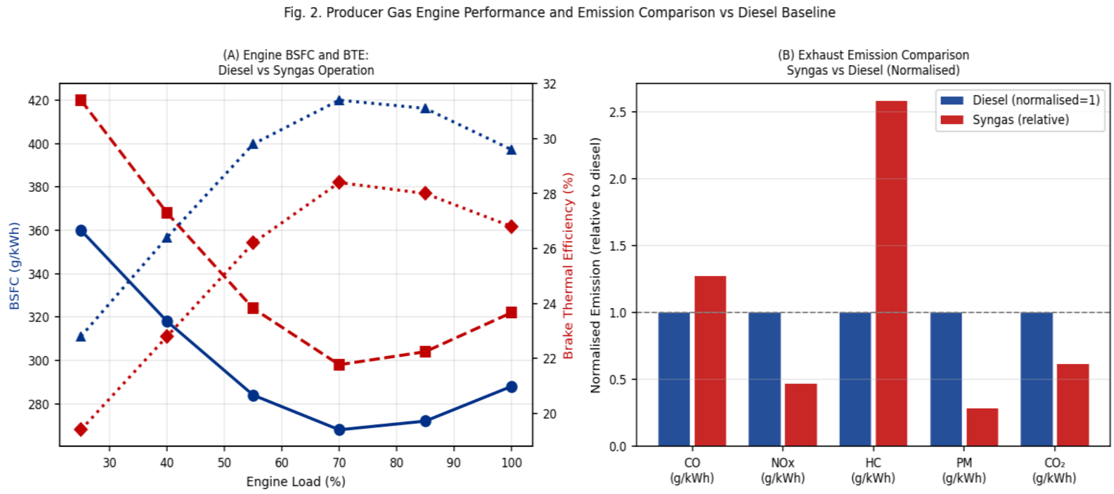

Fig. 2. (A) Engine BSFC and BTE — Syngas vs Diesel across Load Range; (B) Normalised Exhaust Emission Comparison

Table 1. Comparative Gasification Performance — Five Agro-Residue Feedstocks (ER=0.27, T=900°C)

Feedstock	LHV (MJ/Nm^3)	CGE (%)	Tar (g/Nm^3)	CO (%)	H_2 (%)	Specific Gas Yield (Nm^3/kg)
Rice Husk	4.82	68.4	1.84	24.8	16.2	1.84
Bagasse	5.14	72.8	2.12	26.4	17.8	2.04
Wood Chips	5.48	76.2	1.42	28.6	18.4	2.12
Cotton Stalk	4.68	66.4	2.84	23.6	15.4	1.76
Bamboo	5.28	74.6	1.68	27.4	17.6	2.08

All values with dolomite catalytic tar cracking; tar measured by gravimetric IP/CEN method; CGE on LHV basis; gas yield at STP conditions

3.3 Energy Balance and Feedstock Characterisation

Figure 3 Panel A presents the energy balance waterfall for the 20 kWe downdraft system, confirming that 74.2% of biomass input energy reports in the syngas LHV — with losses attributed to moisture evaporation (8.4%), unconverted char and ash (6.2%), tar combustion losses (4.8%), and sensible heat in exit gas (6.4%). This 74.2% cold gas efficiency, achieved with wood chips at optimal operating conditions, exceeds the literature range of 65-70% typically reported for downdraft gasifiers — attributable to the improved char bed design incorporating a recirculation channel that extends char residence time and increases carbon conversion. Panel B's proximate analysis comparison across the five agro-residues confirms wood chips' superiority for gasification (high volatile matter 82.1%, low ash 1.4%) and rice husk's primary challenge (high ash 18.8%) that requires modified throat geometry to manage ash clinker formation.

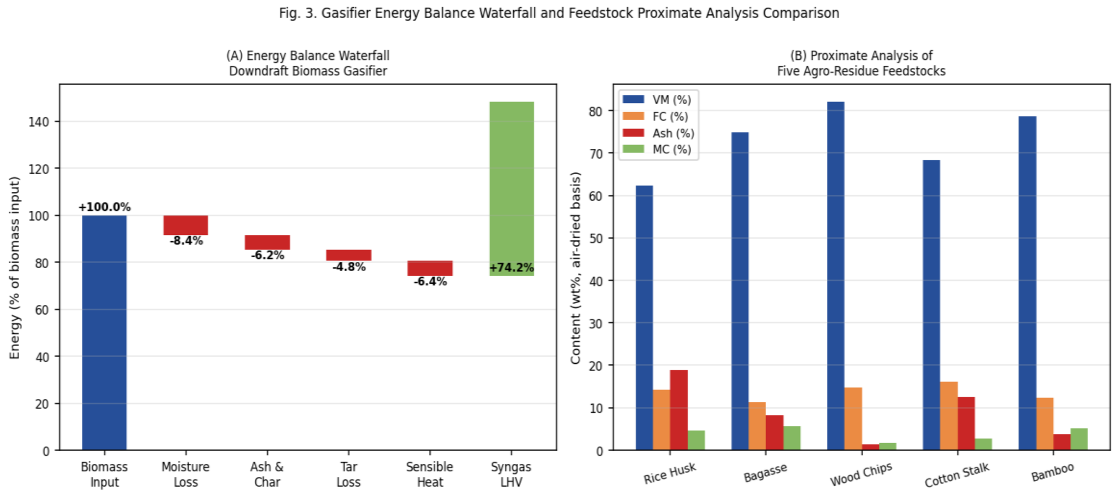

Fig. 3. (A) Energy Balance Waterfall — 20 kWe Downdraft Gasifier (Wood Chips, Optimal Conditions); (B) Proximate Analysis of Five Agro-Residue Feedstocks

4. Discussion and Conclusion

The downdraft biomass gasifier achieves cold gas efficiency of 68-76% across the five feedstocks, with wood chips and bamboo as the best-performing feedstocks and rice husk requiring process adaptation for ash management. The dolomite catalytic tar cracking reduces tar to engine-acceptable levels at 900°C operation, enabling direct use of the cleaned syngas in a modified spark-ignition generator with 28.4% brake thermal efficiency at 70% load — economically viable given syngas's zero fuel cost from agro-residue feedstocks. The ASPEN Plus model from Mälardalen University, calibrated to experimental data with within 8% agreement on syngas composition and CGE, provides a design tool for scaling the system to 100 kWe for agro-processing cluster applications. Future work will extend to fluidised bed gasification for mixed feedstock flexibility and investigate integration with biochar production for soil amendment applications under India's carbon credit framework.

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