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Comparative Air Gasification of Agricultural Residues in an Indigenously Designed Fluidised Bed Gasifier

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ABSTRACT

This study evaluates the performance and operational feasibility of a low-cost, indigenously developed pilot-scale fluidised bed gasifier operated under fixed conditions using multiple biomass feedstocks. The adaptability of the reactor for multi-biomass gasification was assessed using sawdust (SD), wheat straw (WS), rice husk (RH), corn stalk (CS), and spent tea waste (STW). Gasification experiments were carried out in an externally heated fluidised bed reactor using air as the gasifying agent. The reactor was equipped with custom-designed lateral nozzles to ensure uniform air distribution and to minimise particle clogging during prolonged operation. All experiments were conducted at a constant fuel feed rate of 20 kgh^{-1}, operating temperatures between 750 and 950 °C, and equivalence ratios of 0.20, 0.25, and 0.30. Reactor performance was evaluated based on syngas composition (CO, H_2, CH_4), syngas yield, lower heating value (LHV), carbon conversion efficiency (CCE), and cold gas efficiency (CGE). The results showed that at an ER of 0.2, SD produced the highest CO (27.56%) concentration, LHV of 6.57 MJNm^{-3}, and maximum CGE of 76%. STW yielded the highest H_2 (21.45%) and CH_4 (3.39%) contents and syngas yield (2.31 Nm^{3}kg^{-1}) at an ER of 0.3, while CS exhibited the maximum CCE of 82% at an ER of 0.25. CGE values above 60% were obtained for all feedstocks. These findings demonstrate stable reactor operation, effective nozzle performance, and strong adaptability to diverse biomass types. The developed system shows potential for decentralised energy generation and sustainable utilisation of locally available biomass resources.

Keywords: Biomass, carbon conversion efficiency, cold gas efficiency, equivalence ratio, fluidised bed gasifier, lower and higher heating values, syngas yield

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INTRODUCTION

In the last decade, the need for reliable and sustainable energy sources has become more important, particularly in Pakistan. With the growth of industries and populations, energy demand is rising. Previously, the world relied on fossil fuel reserves as the primary and most effective source of energy (Salim et al., 2014). High energy prices have added another layer of complexity for industries worldwide (Horobet et al., 2021). In addition, burning fossil fuels is a major cause of acid rain and greenhouse gas emissions due to the release of CO_2, NO_x, SO_x, and other pollutants, which pose a serious threat to the global climate (Najjar, 2011). A lot of research is being done to use renewable energy sources to partially replace fossil fuels. Renewable resources are the best way to reduce energy hazards and improve environmental and economic sustainability (Latif et al., 2020). Solid waste generation and management are other critical and emerging problems in Pakistan. Traditionally, solid wastes are either dumped in landfills or burned, particularly in the case of agricultural waste such as biomass that produces secondary pollutants which damage health and the environment. Pakistan generated approximately 49.6 million tons of solid waste annually, increasing at a rate of 2.4% per year (Sanjrani et al., 2023). Jabeen et al. (2021) estimated the greenhouse gas emissions generated from domestic solid waste in Faisalabad and suggested its potential use as an energy source for both domestic and industrial applications. Therefore, it is crucial to implement alternative waste management strategies, particularly for biomass, that minimise environmental harm and reduce secondary pollutants (Clauser et al., 2021).

Out of all renewable resources currently studied in Pakistan (solar, hydropower, biomass, and wind), biomass is regarded as the best because of its easy accessibility, constant supply, wider availability and unique environmentally friendly nature (Saghir et al., 2019). In Pakistan, total biomass potential is estimated as 50,000 GW hyr^{-1} (Farooqui, 2014), which accounts for up to 36% of the overall energy scenario of the country (Asif, 2009). According to the source, biomass can be classified into three different types: municipal solid waste (organic waste, garden waste, domestic garbage, etc.), industrial waste (pressing byproducts, etc.) and agricultural and forestry waste (crop residues, forestry processing waste, etc. (Sánchez et al., 2019). Biomass is an enormously available resource, geologically scattered across the globe (Devi et al., 2020).

Among all the potential biomass sources, as an agriculture-based economy, Pakistan produces a significant amount of crop residues, specifically rice husk (RH) and rice straw (RS), which are burned at a rate of 135.38 thousand tons and 307.7 thousand tons after crop harvesting to prepare the land for the next crop that release a harmful gas (Memon, 2022). Normally, rice husk is discarded or used in low-value purposes such as barn mating. Five primary crop residues (wheat straw, rice straw, rice husk, cotton straw, corn stover, and bagasse) were estimated and found that, in 2018, approximately 40 million tons of crop residues were available in Pakistan for power generation, assuming a 50% residue removal factor (Kashif et al., 2020). Safdar et al. (2020) discussed the potential of crop residues as a primary renewable energy source, emphasising their abundant availability in Pakistan. Wheat straw is an abundant agricultural residue that contains high levels of lignocellulose, a key energy source (Nguyen et al., 2013). As a renewable feedstock, it is widely available after wheat harvesting, making it a sustainable biomass resource for energy conversion. Other biomass waste, like sawdust, which is an abundant waste resource obtained on a large scale during industrial processing, requires careful disposal is required for such type of waste. Sawdust is commonly used for various purposes; however, a portion is either openly dumped or burned for heating, leading to environmental issues such as pollution. This poses significant health risks, particularly in developing countries like Pakistan (Batool et al., 2021). Sawdust has been approved for its potential on the syngas composition and gasification performance (Baskara Sethupathy et al., 2012; Chen et al., 2015). Spent Tea Waste (STW) is a high-carbonaceous powdery biomass, which is produced after brewing the tea (Augustine et al., 2021). The global consumption of tea has grown significantly, reaching 6.6 million tons in 2021 (Ben Abdallah et al., 2023). Around 90% of tea consumption results in the generation of tea waste (Tian et al., 2016). In Pakistan, approximately 200,000 metric tons of spent tea waste are produced annually from the consumption of 100 billion cups of tea (Rameeza & Eun, 2022). Tea waste is generally disposed of or used as fertiliser (Raza et al., 2022). However, previous research on the treatment of tea waste, such as pyrolysis, gasification, and carbonisation, remains limited (Xu et al., 2009). Waste-to-Energy (WtE) is one of the strategies to manage and utilise municipal solid waste management (MSW) for energy generation, helping to decrease the dependency on fossil fuels and natural gas. From the previous studies, it has been found that biomass derived from crops, wood, and tea has a great potential for gasification to generate heat and electricity. To the author's knowledge, there is still a lack of studies on the gasification performance of spent tea waste.

Advanced conversion technologies are urgently needed in Pakistan. Biomass energy conversion processes include physical, thermochemical, and biological processes. Thermochemical conversion methods (combustion, gasification, and pyrolysis) (Brown, 2019), have been widely and commercially employed all over the world due to their less wasteful pretreatment process by reducing operational complexity and cost. Among all thermochemical conversion methods, gasification is considered the best due to its high efficiency in converting a wide range of feedstocks (Basu, 2010) and is one of the conventional thermochemical conversion methods (Akyüz et al., 2020). Gasification is a thermochemical process that converts biomass or waste into combustible gases at high temperatures (>650 °C) under controlled oxidising atmospheres. Producer gas primarily contains H_2, CO, CH_4, CO_2, and N_2 (Win et al., 2019; Xue et al., 2014). Biomass gasification is the process of converting carbonaceous material like biomass in a partial oxidation environment in a series of chemical reactions, such as dehydration, devolatilization/pyrolysis, to produce syngas (a combustible fuel) which contains carbon monoxide, hydrogen, methane and hydrocarbons, etc. at a high temperature between 800-1000 °C (Ai et al., 2022). Gasification can be autothermal (direct) or allothermal (indirect). Autothermal gasifiers use part of the fuel for internal heat, while allothermal systems require an external heat source (Heidenreich & Foscolo, 2015).

Currently, various types of gasification reactors are available: fixed bed, entrained bed, and fluidised bed (Kordi & Seyyedi, 2021). Several factors influence the selection, including technology, heat load, types of materials, energy consumption, the environment, and economics. Although fixed beds, which include up-, down-, and cross-drafts, are the classical type of the gasifier, they are limited in their ability to use non-uniform fuel sizes and thermal load variations. Fluidised bed reactors, which can burn fine solid fuels with non-uniform sizes more rapidly, have been used recently in thermal industries, particularly in medium-sized power plants. Its fuel flexibility enables isothermal operating conditions and ensures highly efficient energy conversion with low tar (Buragohain et al., 2010; Sidek et al., 2020). A fluidised bed gasification reactor comprises a cylinder-like column filled with a bed material, typically inert sand, supported by a perforated plate with evenly distributed nozzles. Primarily, the sand bed is initially heated using an external heat source to facilitate the gasification process. Air, oxygen, and steam are utilised as oxidising agents, facilitating the fluidisation of bed materials and enabling the partial oxidation of biomass feedstock within a temperature range of 700-900 °C (Buragohain et al., 2010). The choice of gasifying agent affects syngas composition and heating value. Air is cost-effective and operationally simple, whereas oxygen–steam mixtures yield hydrogen-rich gas with higher LHV (Shayan et al., 2018).

Mahapatro and Mahanta (2020) examined low-grade coal, sawdust, and rice husk in a pressurised circulating fluidised bed gasifier. Increasing pressure improved CCE (54-97%), CGE, and gas yield. Ali et al. (2024) examined air gasification of municipal solid waste components (wood, paper, and cloth) in an atmospheric fluidised bed gasifier by varying equivalence ratio (0.2-0.5), temperature (800-950 °C), and $CaCO_3$ addition. Higher temperatures enhanced CO and H_2 production, LHV, and CCE, whereas increasing ER increased CO_2 yield and CCE while reducing syngas yield and LHV; $CaCO_3$ addition at 900 °C promoted syngas formation, suppressed CO_2, and achieved a maximum LHV of ~8000 kJ Nm^{-3} for wood gasification. Mohanty et al. (2025) studied pinewood air gasification in a lab-scale fluidised bed with dolomite, limestone, and activated charcoal. CCE and CGE increased with temperature (700-850 °C) and ER (0.20-0.35), reaching complete carbon conversion around ER ≈ 0.30–0.35. Tar content was reduced via activated carbon. Mallick et al. (2020a, 2020b) reported air-blown co-gasification of rice husk, sawdust, and bamboo dust in a 50-kW circulating fluidised bed. ER (0.19–0.35) and temperature (800-900 °C) effects were evaluated. Higher ER increased gas yield, CCE, and CGE, while reducing CO and H_2 concentrations and LHV. Biomass blending enhanced CCE up to 98% and CGE to 62%. Cvetinović et al. (2024) reported that gasification is more favourable at low air-to-fuel and steam-to-fuel ratios, consistent with previous studies. Badu et al. (2025) studied a 200 kW semi-industrial air-blown fluidised bed. Increasing ER (0.22-0.45) improved bed temperature, gas yield, CCE (78.6-98.5%), CGE (51.8-71.4%), and overall efficiency (79-93%), while reducing syngas LHV (3.9-7.1 MJ/Nm^3) due to nitrogen dilution. Other works have demonstrated the importance of fluidised bed hydrodynamics, including air distributor and nozzle geometry, in improving particle motion, bed mixing, and pressure stability (Alashmawy et al., 2024; Raza & Ahsan, 2024; Tian et al., 2024). Yet, validation under actual gasification conditions remains limited.

Although substantial research has been conducted on fluidised bed gasification, several practical and operational challenges remain insufficiently addressed. One of the most critical issues is nozzle clogging and biomass agglomeration, which disrupt uniform air-biomass mixing, reduces effective mass and heat transfer, and ultimately degrades gasifier performance. These operational limitations are particularly pronounced in long-duration and pilot-scale operations. In Pakistan, very few studies have been reported on indigenously developed pilot-scale fluidised bed gasifiers. Most experimental investigations rely on imported or commercially purchased reactors, which significantly increase research costs and limit design adaptability to local biomass characteristics and operating conditions. Consequently, limited attention has been given to developing gasifier designs tailored to local resources, feedstock variability, and economic constraints. Furthermore, most of the existing literature focuses on laboratory-scale gasifiers, often investigating a single biomass type or a narrow operating window. Comparative gasification studies involving multiple biomass feedstocks under identical operating conditions remain scarce, particularly at the pilot scale.

These gaps highlight the need for low-cost, indigenously designed pilot-scale fluidised bed gasifiers that can ensure reliable operation, improved air distribution, and uniform heat transfer while accommodating a wide range of biomass feedstocks. Addressing these challenges provides the motivation for the present study, which aims to enhance reactor design and operational feasibility under realistic and locally relevant conditions.

This study investigates the air-gasification performance of five different biomass feedstocks (agricultural residues), such as sawdust (SD), wheat straw (WS), rice husk (RH), corn stalk (CS), and spent tea waste (STW), in an allothermal, indigenously designed, low-cost, and efficient pilot-scale fluidised bed gasifier. The laterally arranged nozzles are radially distributed over a perforated plate to prevent blockage by inert materials. Experiments were conducted over an equivalence ratio (ER) range of 0.20-0.30 within a temperature range of 750-950°C, focussing on syngas composition, yield, lower heating value (LHV), higher heating value (HHV) of syngas, cold gas efficiency (CGE), carbon conversion efficiency (CCE), and overall reactor performance.

MATERIALS AND METHODS

Feedstocks Selection and Collection

The feedstocks utilised in this study included sawdust, wheat straw, rice husk, corn stalk and spent tea waste based on availability. Sawdust was sourced from various sawmills and carpenter shops, while crop residues, including wheat straw, rice husk, and corn stalk, were obtained from fields after harvesting. Spent tea waste was obtained from tea hotels and small tea shops, where it is generated in substantial quantities. All feedstocks were collected from Faisalabad due to its abundance of biomass potential resources, and many industrial activities in this region generate a ton of waste every year while processing the crops.

Pretreatment of Feedstocks

Pretreatment was done at the Agricultural Engineering Workshop, University of Agriculture, Faisalabad (UAF). Each ungrounded biomass feedstock was stored in an individual bag. Each biomass was then spread on an open field for two days under an open-air sun drying process. Spent tea waste was soaked to remove externally introduced beverage additives (milk and sugar) before drying, ensuring consistent and representative biomass behaviour during gasification while leaving the primary lignocellulosic structure largely unchanged and subsequently dried in a solar drier. After that, the wheat straw and corn stalks were chopped due to their larger particle size to achieve the required particle size suitable for grinding. All feedstocks were then ground using a grinder and then sieved to obtain a particle size between 0.2 mm and 1.5 mm, as shown in Figure 1. All biomass feedstocks were then stored at the Material Testing Laboratory storage facility under standard conditions, such as a dry and cool environment with controlled moisture levels and under well-ventilation to prevent degradation or contamination from microbial activities until laboratory-scale investigation and experimentation.

Properties of Feedstocks

Silica sand was utilised as the bed material in this study because it ensures uniform fluidisation, temperature, and heat-transfer effects in a gasifier, and it is very inexpensive. The mean particle sizes, apparent densities, bulk densities, and porosities of the silica sand and feedstocks are shown in Table 1.

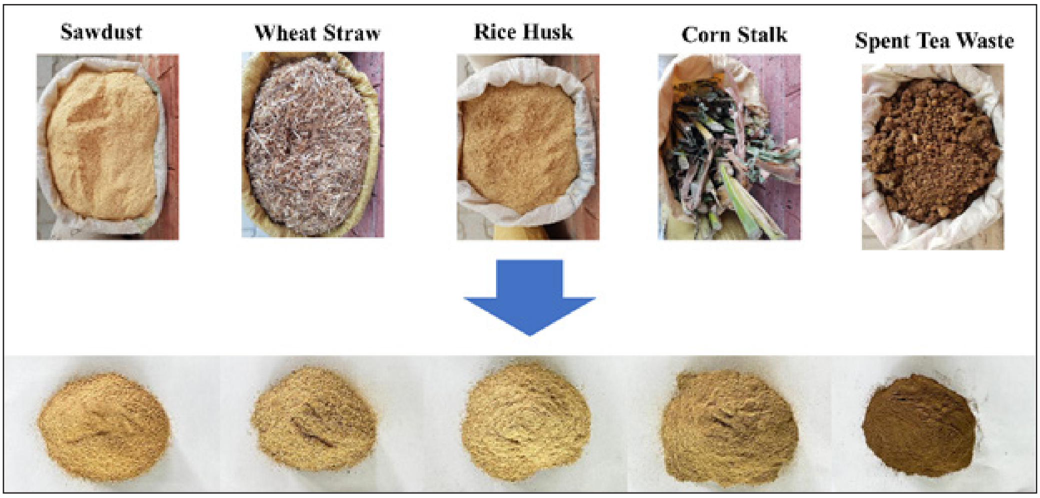


Figure 1. Pre-treatment of biomass feedstocks

Table 1
Properties of biomass feedstocks and bed material

Properties	Silica sand	Sawdust	Wheat Straw	Rice Husk	Corn Stalk	Spent Tea Waste
Mean particle size (µm)	384	467	434	576	678	386
Apparent density (kgm^{-3})	2630	1300	1350	1510	1330	1233
Bulk density (Kgm^{-3})	1602	259	188	264	233	273
Porosity	0.4	0.8	0.86	0.83	0.82	0.78

Characteristics of Feedstocks

Chemical compositions of these feedstocks were determined by the proximate and elemental analysis as presented in Table 2. Proximate analyses were performed in the Densification Laboratory, Department of Agricultural and Biological Engineering (ABE), the Pennsylvania State University, PA 16801, United States of America. Elemental analysis was done at the Iowa State University Chemical Instrumentation Facility (1240 Hach Hall), in the United States of America. All analyses were conducted before the combustion of the biomass feedstocks.

Experimental Setup

All experiments were conducted using an indigenised fluidised bed gasification reactor, which is situated at the solar park in front of the Material Testing Laboratory, Structures and Environmental Engineering, Agricultural Engineering Workshop, University of

Table 2
Proximate and elemental analysis of biomass feedstocks

Parameters	Sawdust	Wheat Straw	Rice Husk	Corn Stalk	Spent Tea Waste	Standards/References
Proximate						
Moisture contents (wt.%, adb)	9.65	6.08	6.85	6.97	6.77	(ASTM)-E-871-82
Volatile matter (wt.%, adb)	67.51	58.12	62.33	66.5	71.25	
Ash (wt.%, adb)	19.88	15.44	14.83	18.78	17.57	LAP
Fixed carbon (wt.%, adb)	2.96	20.36	15.99	7.75	4.41	(Alakangas, 2016)
Elemental						
C (wt.%, adb)	46.113	41.397	41.082	42.109	47.105	CHNS/0 Analyser
H (wt.%, adb)	5.695	5.512	5.674	5.387	6.51158	
N (wt.%, adb)	0.7125	0.65823	1.72104	0.972	3.94698	
S (wt.%, adb)	0	0	0	0	0.54299	
O (wt.%, adb)	47.480	52.433	51.526	51.533	41.894	(Bridgeman et al., 2010)
Higher heating value ($MJkg^{-1}$)	17.662	16.662	16.015	18.282	21.981	(Manual, 2008)
Lower heating value ($MJkg^{-1}$)	16.29	15.4	14.71	17.03	20.5	(Basu, 2010)

Agriculture, Faisalabad. A process diagram of an indigenised fluidised bed gasification reactor is shown in Figure 2.

A reactor was designed with a height of 1.524m and a diameter of 0.1524m, equipped with components like a blower, heater, plenum, distributor plate, nozzles, hopper, screw feeder, cyclone, and gas filter. All materials were locally available, and no complex components or high-cost systems were required, ensuring low capital expenditure. The distributor plate was equipped with specially designed 19 vertical nozzles to ensure effective air-fuel interaction within the reactor. Each nozzle contains two lateral openings positioned symmetrically on the left and right sides, along with a central bottom opening through which preheated air is introduced into the bed. Before each experiment, the inlet and outlet conditions of individual nozzles were carefully adjusted to verify even air distribution throughout the system. In addition, the syngas composition remained stable during prolonged steady-state operation, providing further evidence that air was evenly supplied to all nozzles throughout the gasification process. This configuration promotes uniform distribution of the gasifying agent, leading to improved mixing between the biomass fuel and air. As a result, stable reaction conditions are achieved while minimising the risks of bed clogging and particle agglomeration.

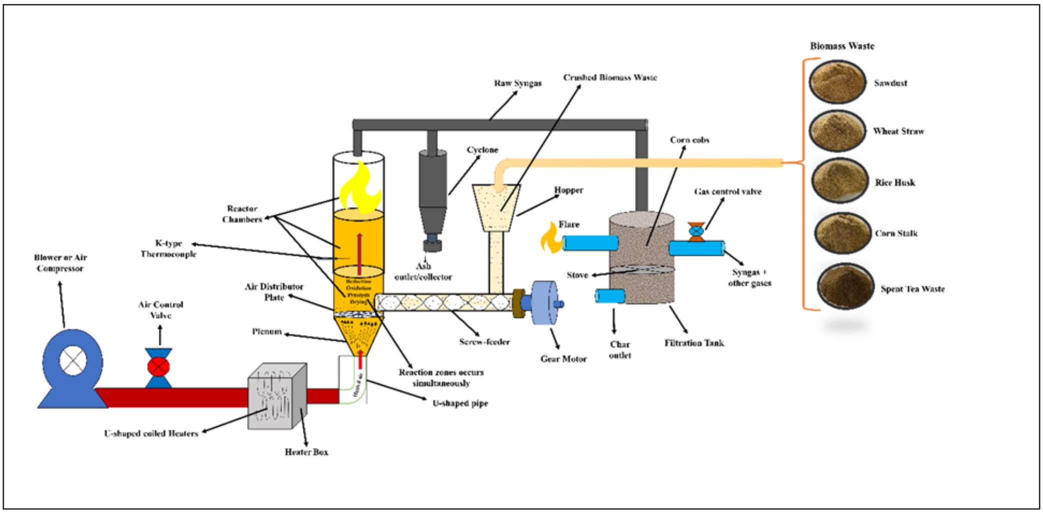


Figure 2. Process diagram of an indigenised fluidised bed gasification reactor

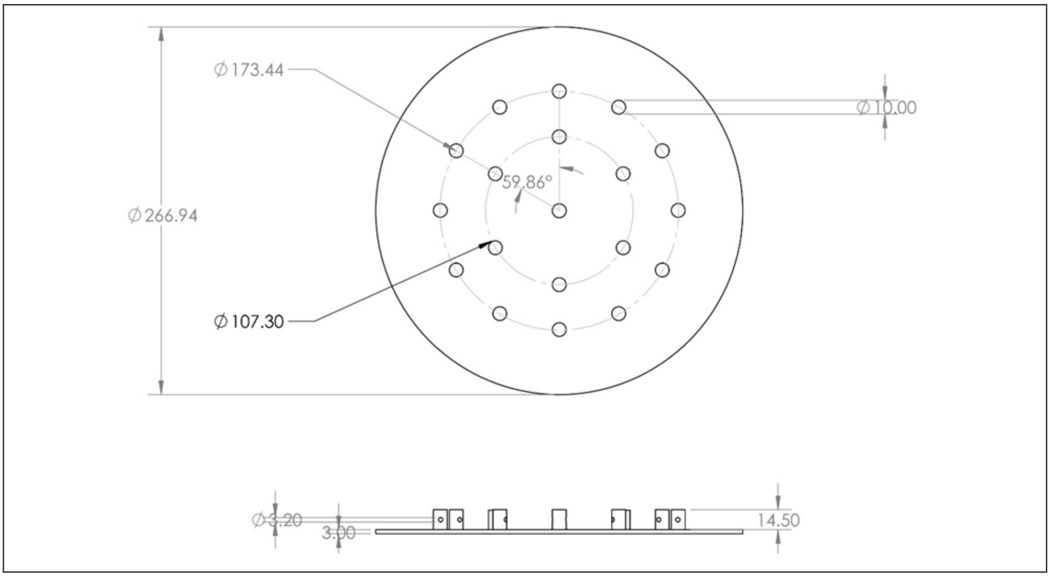


Figure 3. Distributor plate with vertical nozzles and dimensions

Furthermore, the nozzle geometry enhances the local air velocity, which supports homogeneous fluidisation and consistent reaction kinetics. The detailed arrangement and dimensions of the nozzles mounted on the distributor plate are illustrated in Figure 3.

The reactor was fabricated from mild steel. A complete photograph of the experimental setup, together with an AutoCAD drawing with labelled components, is shown in Figure 4. The dimensions of the setup are given in Table 3.

The experiments were conducted at three different ERs, 0.20, 0.25 and 0.30, with a constant feed rate of 20 kgh^{-1} to evaluate how different biomass types affect gasification performance. Based on operational stability considerations, the equivalence ratio (ER) was selected in the range of 0.2-0.3. Previous studies have shown that ER values below 0.2

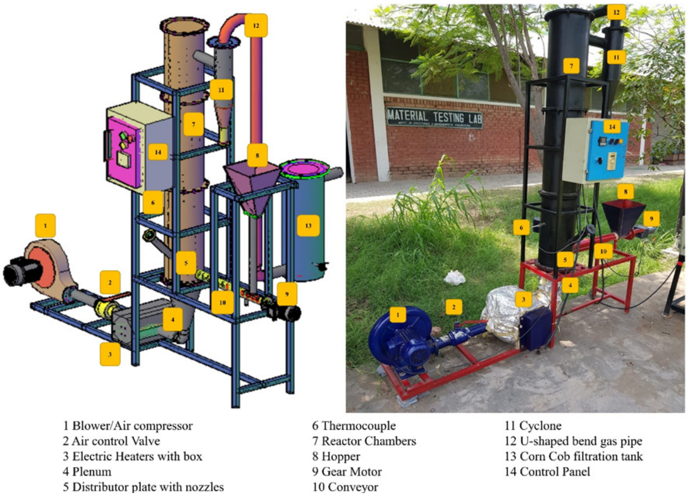


Figure 4. Complete experimental setup of the fluidised bed gasifier with labelled AutoCAD drawing

Table 3
Design specifications and dimensions of the FBG Reactor

Description	Dimensions
Reactor Cylinder	Dia. 152.4 mm, Height 1524 mm
Cyclone	Length 609 mm, Dia. 101 mm
Gear Motor	90 hp, 70 rpm, 220 V
Hopper	Square in shape, H 254 mm, top L or W 279.4 mm, bottom L 127 mm W 114.3 mm Capacity 2 kg, 45°
Conveyor	Dia. 12.7 mm, Length 609 mm
Blower	3 hp, 2800 rpm
Air Control Valve	Manually operated, Opening Dia. 50.8 mm
Heater	4 heaters, 1500 Watt each, 220 V
Plenum	Upper Dia. 203 mm, Bottom Dia. 50.8 mm
Distributor Plate	Dia. 203 mm, Thickness 6.35 mm
Nozzles	19 Nozzles, Dia. 10 mm, Lateral holes Dia. 1.2 mm Bottom hole Dia. 3.2 mm
Frame	H 1824 mm, L 1676 mm
Filtration Cylinder	H 635 mm, Dia. 228 mm
Ash Collector	Dia. 50.8 mm

result in an insufficient oxygen supply, which can lead to unstable ignition and incomplete gasification. Conversely, increasing the ER beyond 0.3 introduces excess oxygen, promoting excessive oxidation and shifting the process toward combustion, which may deteriorate syngas quality, as reported in (Jamin et al., 2020a). Although some studies have employed ER values up to 0.35, such investigations typically utilise catalytic bed materials that enhance tar reforming and water-gas shift reactions, allowing stable operation at higher ER. Therefore, an ER range of 0.2-0.3 was chosen in the present study. At the start-up of the experiment, the gasifier was charged with 5 kg of silica sand used as bed material to provide a good heat transfer and uniform fluidisation with a velocity of fluidization at 0.176 ms^{-1}. A hopper consists of Sawdust, Wheat straw, Rice husk, Corn stalk and Spent tea waste, which were fed into the fluidised bed gasifier through a screw feeder, respectively, as a feedstock with the feeding rate of 20 kgh^{-1}. The reactor had a maximum rated thermal capacity of 114 kWh. The thermal capacity of the gasifier for each biomass was calculated individually using its lower heating value and a fixed feed rate, as summarised in Table 4, demonstrating that the system functions at a pilot scale.

Air being a gasifying agent coming from the blower or air compressor (2800 rpm) with air speed from 8-15 ms^{-1} measured from AM-4812 anemometer device for each biomass feedstocks was first heated by the four U-shaped coiled electric heaters enclosed in the box which is fitted on its way to increase the temperature of the air up to 400^{o}C in 20-30 minutes depends upon the speed of ambient air surrounding it and passes it through the nozzles holes from the plenum distributed on the distributor plate and it starts burning of the biomass at the temperature of 750-950^{o}C to carry out the gasification process. No nozzle blockage or airflow restriction was observed during 3–4 hours of uninterrupted reactor operation for any of the tested biomass feedstocks. Maintain the gasification process by monitoring the temperature. During steady-state operation, the reactor bed temperature was maintained within ±15^{o}C, while variations in hydrogen and carbon monoxide concentrations remained within ±5 vol%. Proper fluidisation was confirmed through theoretical analysis and experimental observation. In all experiments, the superficial gas velocity exceeded the minimum fluidisation velocity (U_{mf} = 0.089–0.152 ms^{-1}), resulting in stable bed operation.

Table 4

Thermal capacity of the gasifier for various biomass feedstocks

Biomass	Feed Rate (kg/h)	LHV (kJ/kg)	Thermal Capacity (kW)
Sawdust	20	16290	91
Wheat Straw	20	15400	86
Rice Husk	20	14710	82
Corn Stalk	20	17030	95
Spent Tea Waste	20	20500	114

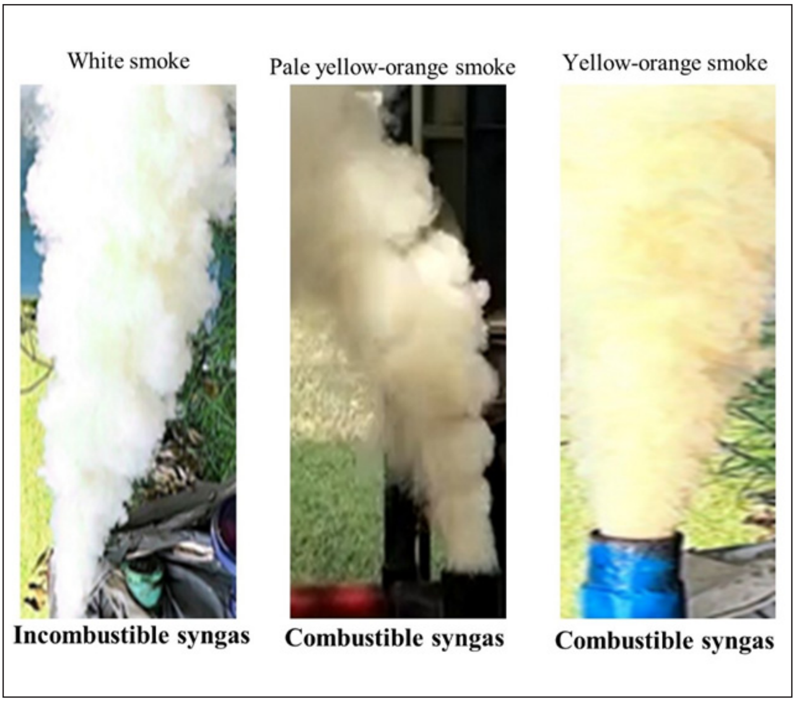


Figure 5. Comparison of syngas colour and combustibility

Visual observations showed uniform bed expansion and stable bubbling without channelling or stagnant zones. Consistent operating conditions ensured reliable fluidisation for all biomass feedstocks. A flame emerges from the flare stack stove, indicating the reactor is producing syngas. Ensure the reactor reaches targeted temperatures of (850-950°C, 750-850°C) and make sure syngas is neither too "tarry" nor too "sooty". Figure 5 shows a comparison of syngas combustibility based on the observed smoke colours.

Syngas quality was qualitatively evaluated based on flame stability, flame colour, and smoke emission characteristics during gasification experiments. Gasification (incomplete combustion of carbonaceous fuels) can be expressed using the sub-stoichiometric shows in Equation 1:

$$\text{Biomass} + \text{Limited Air} \rightarrow CO + H_2 + CH_4 + CO_2 + H_2O + N_2 \qquad [1]$$

To collect the syngas, air sampling bags were used and flushed before opening the valve at the gas outlet of the system. Attach the air sampling bag to the outlet port of the hand pump using a coupling, pump the required amount of syngas into the bag, and seal it for gas chromatography analysis. Gas chromatography measurements had an estimated uncertainty of ±2–5%, with ±3% used for error propagation. Uncertainty in LHV, HHV,

Table 5
Chain of chemical reactions involved in the biomass gasification process

Reaction Type	Reaction Equation	Enthalpy	Reactions
Endothermic		ΔH (kJ/mol)	
Pyrolysis	Dry feedstock + heat → char + volatiles	--------	R1
Water-gas/ Steam Gasification	C [volatiles/char] + $H_2O \rightarrow CO + H_2$	+131.4	R2
Boudouard/Reduction Reaction	C [volatiles/char] + $CO_2 \rightarrow 2CO$	+172	R3
Water-Gas Shift (WGS) reaction	$CH_4 + H_2O \leftrightarrow 4CO + 3H_2$	+206	R4
Exothermic			
Oxidation Reaction	$C + O_2 \rightarrow CO_2$	-406	R5
	$2H_2 + O \rightarrow 2H_2O$	-242	R6
Methanation Gasification	$C + 2H_2 \leftrightarrow CH_4$	-75	R7
Water-Gas Shift (WGS) reaction	$CO + H_2O \leftrightarrow CO_2 + H_2$	-42.3	R8

CGE, and CCE was calculated using the root-sum-square method. Shut down the system by closing the gas out and air inlet valves. Finally, allow the system to cool down completely.

All the chemical reactions that occur inside the gasifier are discussed in Table 5. In the first zone, drying removes moisture from the biomass at 150-200 °C. This is followed by pyrolysis (R1) (200-500 °C), where biomass decomposes in an oxygen-deficient environment to produce char, tars, and volatile gases. In the oxidation zone (R5-R6) (800-1200 °C), partial combustion of char and volatiles with limited oxygen generates CO_2 and H_2O, releasing heat to sustain the endothermic gasification reactions. Finally, in the reduction zone (700-1000 °C), char reacts with H_2O and CO_2 through the Boudouard (R3) and water–gas reactions (R2), while the water-gas shift (R8) and methanation (R7) reactions further influence the syngas composition. As a result, the producer gas primarily consists of CO, H_2, CO_2, and CH_4.

Gasification Performance Metrics

Equivalence Ratio (ER)

The equivalence ratio (ER) is defined as the ratio of the actual oxygen-to-biomass ratio to the stoichiometric oxygen-to-biomass ratio required for complete combustion. This relationship is expressed in Equation 2, (Lv et al., 2003).

$$\mathrm{ER} = \frac{\text{Weight of oxygen (air)/Weight of dry biomass}}{\text{Stoichiometric oxygen (air)/Biomass ratio}} \qquad [2]$$

Lower Heating Value of Syngas

(LHV_{syngas}) refers to the chemical energy in MJ contained per unit of volume of the syngas, which is calculated according to the combustible components present in the syngas by using Equation 3, (Guo et al., 2014; Wan et al., 2013).

$$LHV_{syngas} = \frac{[12.622(\%H_2) + 10.788(\%CO) + 35.814(\%CH_4)]}{100} \; (MJNm^{-3}) \qquad [3]$$

Higher Heating Value of Syngas

High heating value of syngas (HHV_{syngas}) is the total amount of heat energy released when a unit mass of syngas is completely burned. HHV_{syngas} can be calculated by the below-mentioned Equation 4, (Wan et al., 2013).

$$HHV_{syngas} = \frac{[(\varkappa_1 \cdot HHV)_{CO} + (\varkappa_3 . HHV)_{H_2} + (\varkappa_4 \cdot HHV)_{CH_4}]}{100}$$

OR [4]

$$HHV_{syngas} = (H_2\% \times 30.52 + CO\% \times 30.18 + CH_4\% \times 95) \times 4.19$$

where, '$\varkappa_1, \varkappa_3, \varkappa_4$' represent the volume fractions or percentages of CO, H_2, and CH_4, respectively. The higher heating values (HHV) of CO, H_2 and CH_4 are 12.71 $MJNm^{-3}$, 12.78 $MJNm^{-3}$, and 39.76 $MJNm^{-3}$, respectively.

Syngas Yield (Y_{syngas})

Syngas yield quantifies the volume or mass of produced syngas relative to the biomass feedstock input. It provided insight into the effectiveness of gasification in generating usable gas. The overall dry gas volume generated can be determined using Equation 5 (Guo et al., 2014; Wang et al., 2015), based on the nitrogen concentration in the product gas and the overall nitrogen introduced into the reactor through the air supply during gasification.

$$Y_{syngas} = \frac{Q_a \times \chi_{N_2}}{\chi'_{N_2}} \qquad [5]$$

χ_{N_2}= represents the percentage fraction of N_2 in air under standard conditions, 78.12%

χ'_{N_2}= the volume percentage fraction of N_2 in the product gas at standard conditions, vol.%

Q_a= refers to the volume of air supplied per kilogramme of biomass, Nm^3kg^{-1}
[Volumetric air flow rate (m^3h^{-1}) ÷ Feed Consumption rate (kgh^{-1})

Carbon Conversion Efficiency (CCE)

The carbon conversion efficiency (CCE) refers to the proportion of carbon from the biomass that is transformed into carbon-based gaseous compounds relative to the total carbon content in the biomass. It was calculated as the ratio of the carbon contents in the syngas to the initial amount of carbon contents in the biomass feedstock, expressed as a percentage. Consequently, the carbon conversion efficiency can be determined using Equation 6 (Makwana et al., 2015; Sharma et al., 2011; Wang et al., 2015).

$$\text{CCE (\%)} = \frac{12(\text{CO\%} + \text{CH}_4\% + \text{CO}_2\% + \text{nC}_\text{n}\text{H}_\text{m}\%)}{22.4 \times \%\text{C}_{\text{feedstock}}} \times \text{Y}_{\text{syngas}} \times 100\% \qquad [6]$$

in which,

CCE = Carbon Conversion Efficiency (%)

Y_{syngas} = Yield of dry syngas per kilogramme of dry biomass feedstock (Nm^3kg^{-1})

$\%C_{feedstock}$ = Carbon percentage in the dry biomass feedstock, determined through elemental analysis and CO_2, CO, CH_4, C_nH_m are the volumetric percentages present in the syngas

Cold Gas Efficiency (CGE)

Cold Gas Efficiency (CGE), expressed as a percentage, represents the amount of chemical energy present in the product gas relative to the original energy stored in the solid fuel. This efficiency metric is calculated based on the Lower Heating Value (LHV_f) of the feedstock, which accounts for the energy released during the combustion process, excluding the latent heat of water vapour produced in the reaction. Cold gas efficiency was calculated by Equation 7 (Serrano et al., 2016).

$$\text{CGE (\%)} = \frac{100 \times \text{V}_{\text{syngas}} \times \text{LHV}_{\text{syngas}}}{\text{LHV}_\text{f}} \qquad [7]$$

where 'V_{syngas}' represents the specific gas yield (Nm^3 gas per kg of feedstock) and is determined using Equation 8:

$$\text{V}_{\text{syngas}} = \frac{\text{m}_{\text{syngas}}}{\rho_{\text{syngas}}} \qquad [8]$$

where m_{syngas}, represents the specific mass of the syngas (kg gas kg^{-1} feedstock) and ρ_{syngas} is the density of the syngas (kg gas Nm^{-3} gas). The values of the m_{syngas} and ρ_{syngas} was obtained at Normal Temperature and Pressure (NTP) using Equation 9 and 10, as follows (Susastriawan et al., 2019b).

$$m_{syngas} = \frac{MW_{syngas}}{n} \qquad [9]$$

$$\rho_{syngas} = \frac{[(\varkappa_1 \cdot \rho)_{CO} + (\varkappa_2 \cdot \rho)_{CO_2} + (\varkappa_3 . \rho)_{H_2} + (\varkappa_4 \cdot \rho)_{CH_4} + (\varkappa_5 \cdot \rho)_{N_2}]}{100} \qquad [10]$$

At Normal Temperature and Pressure (NTP), the densities of the compounds are; ρ_{CO} = 1.165 kgNm^{-3}, ρ_{H_2}= 0.089 kgNm^{-3}, ρ_{CH_4}= 0.668 kgNm^{-3}, ρ_{CO_2}= 1.842 kgNm^{-3}, and ρ_{N_2}= 1.165 kgNm^{-3}

Where, '$\varkappa_1$ to $\varkappa_5$' are volume fractions or percentage of CO, CO_2, H_2, CH_4, and N_2, respectively.

Meanwhile, the volume fractions of CO, CO_2, H_2, CH_4, N_2 in the syngas, along with the global biomass gasification reaction and mass balance, the molar quantity of the feedstock (n) and the molecular weight of syngas (MW_{syngas}) can be determined through Equation 11 and 12.

$$n(CH_xO_yN_z) + m\varphi(O_2 + 3.76N_2) \rightarrow \varkappa_1 CO + \varkappa_2 CO_2 + \varkappa_3 H_2 + \varkappa_4 CH_4 + \varkappa_5 N_2 \qquad [11]$$

$$MW_{syngas} = \frac{[(\varkappa_1 \cdot MW)_{CO} + (\varkappa_2 \cdot MW)_{CO_2} + (\varkappa_3 . MW)_{H_2} + (\varkappa_4 \cdot MW)_{CH_4} + (\varkappa_5 \cdot MW)_{N_2}]}{100} \qquad [12]$$

where 'n' is molar number (moles) of the feedstock, which is expressed as the mass of the feedstock in kg to the molar mass of the feedstock in kgmol^{-1}, 'ϕ' is the equivalence ratio.

RESULTS AND DISCUSSION

Effect of Volumetric Air Flow Rate on the Equivalence Ratio

The equivalence ratio (ER) is defined as the mass ratio of the gasifying agent (air) to the biomass feedstock in a combustion system. In gasification, both the volumetric and mass air flow rates are crucial in determining the ER, as they directly influence the air-to-fuel mixture and combustion characteristics across various biomass types.

Figure 6 illustrates the relationship between the equivalence ratio (ER) and both volumetric air flow rate (m^3h^{-1}) and mass air flow rate (kgh^{-1}) in a gasification system. Both mass and volumetric air flow rate show a consistent increasing trend, ranging from 18-28 kgh^{-1} and 18-24 m^3h^{-1}, respectively, as ER increases from 0.20-0.30. This shows that a higher ER results in greater air supply. These ERs were calculated based on the biomass chemical composition in the methodology section.

Equivalence ratio directly depends on the air flow rate. In most of the studies, ER is maintained by adjusting the air and fuel supply. In this study, variation in air supply while holding other operating variables constant and adjusting it according to ER (0.2,0.25 and 0.3). This approach is widely accepted for fluidised bed gasifiers and medium-to-large-scale fixed bed gasifiers. ER is regulated by adjusting the air flow rate, where a higher ER requires an increased air supply, leading to an enhanced oxidation rate in the gasifier, as observed in previous studies (Upadhyay et al., 2019). At higher air volume per unit time by offering more oxygen into the reactor, thereby promoting complete combustion, which may result in an increase in syngas production. Lower ER makes less oxygen available for the gasification reaction to complete, thus affecting the gas composition with either value of ER (Esfahani et al., 2012). On the other hand, a lower volumetric air flow rate will result in lower ER. There may be incomplete gasification leading to lower syngas yield.

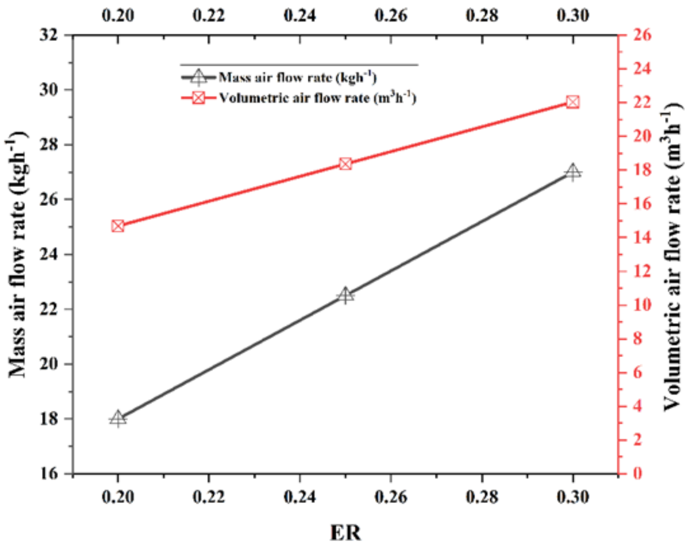


Figure 6. The relation between the mass air flow rate and the volumetric air flow rate with ER

Effect of Equivalence Ratio on the Syngas Compositions (A Combustible Gases)

The effect of the equivalent ratio on syngas composition was studied on various biomass feedstocks. Figure 7 (a-e) present the results of syngas compositions from gasification of sawdust, wheat straw, rice husk, corn stalk and spent tea waste by varying ER (0.20,0.25, and 0.30) at the gasification temperature ranging between 750 °C and 950 °C. Observed trends showed that the contents of CO_2, H_2, and CH_4 in the syngas composition decrease by increasing the equivalence ratio from 0.20 to 0.30. It is seen that the CO contents in the syngas in the gasification of sawdust were higher, of 27.56% at an equivalence ratio of 0.2, than those from the gasification of corn stalk, wheat straw, spent tea waste and rice husk, as 23.89, 23.45, 23.12 and 21.45%, respectively. For H_2 contents, it is higher in the gasification of spent tea waste as 21.45% at an equivalence ratio of 0.2 in comparison to 21.22, 20.48, 20.47 and 18.76% for sawdust, wheat straw, corn stalk and rice husk, respectively. The contents of CH_4 from gasification of the spent tea waste and wheat straw were reported as the highest at an equivalence ratio of 0.2, which is 3.39 and 3.16 %, respectively, as compared to the gasification of other biomass feedstocks such as corn stalk, sawdust and rice husk, at 2.91, 2.56 and 2.42 %, respectively.

Syngas compositions highly depend on the equivalence ratio. The percentage composition of syngas (CO, H_2, CH_4) depends on thermochemical reactions that take place inside the reactor. These chemical reactions are highly affected by the variation in design and operational parameters such as reactor design and size, feedstock type, moisture and ash contents present in the feedstock, equivalence ratio, etc. Present study revealed decreasing trends of carbon monoxide and hydrogen with the increasing ER means more oxygen fed into the fluidised bed gasification reactor leading to enhanced oxidation of hydrogen to form water resulting lower hydrogen production and carbon monoxide to form carbon dioxide thereby reducing level of carbon dioxide in the syngas composition i.e., ($H_2 + ½O_2 \leftrightarrow H_2O$) and ($CO + ½O_2 \leftrightarrow CO_2$) (Basu, 2010). Similar trends have been seen in the previous study (Untoria et al., 2024). The rate of carbon monoxide production in the water-gas reaction is higher than that of hydrogen and methane. Reaction rate sequences are Water Gas Shift > Bouduard > > Methanation reaction (Sikarwar et al., 2016). Therefore, it is reasonable that the CO has the highest percentage fraction in the syngas for all five biomass feedstocks at the observed equivalence ratio. In the case of methane, its composition increases at 0.2 equivalence ratio, but methane gas composition decreases when the equivalence ratio is increased beyond 0.24. This happens due to the oxidation of methane, in which methane is reacted with oxygen coming from the air through a blower, converting into carbon dioxide and steam ($CH_4 + 2O_2 \leftrightarrow CO_2 + 2H_2O$) (Basu, 2010). Methanation reaction is the slowest, and methane production is the lowest in the syngas from the gasification of all biomass feedstocks, i.e., less than 4%, similar as reported in earlier studies (Susastriawan et al., 2019a). A higher value of equivalence ratio represents more methane burns, thus reducing

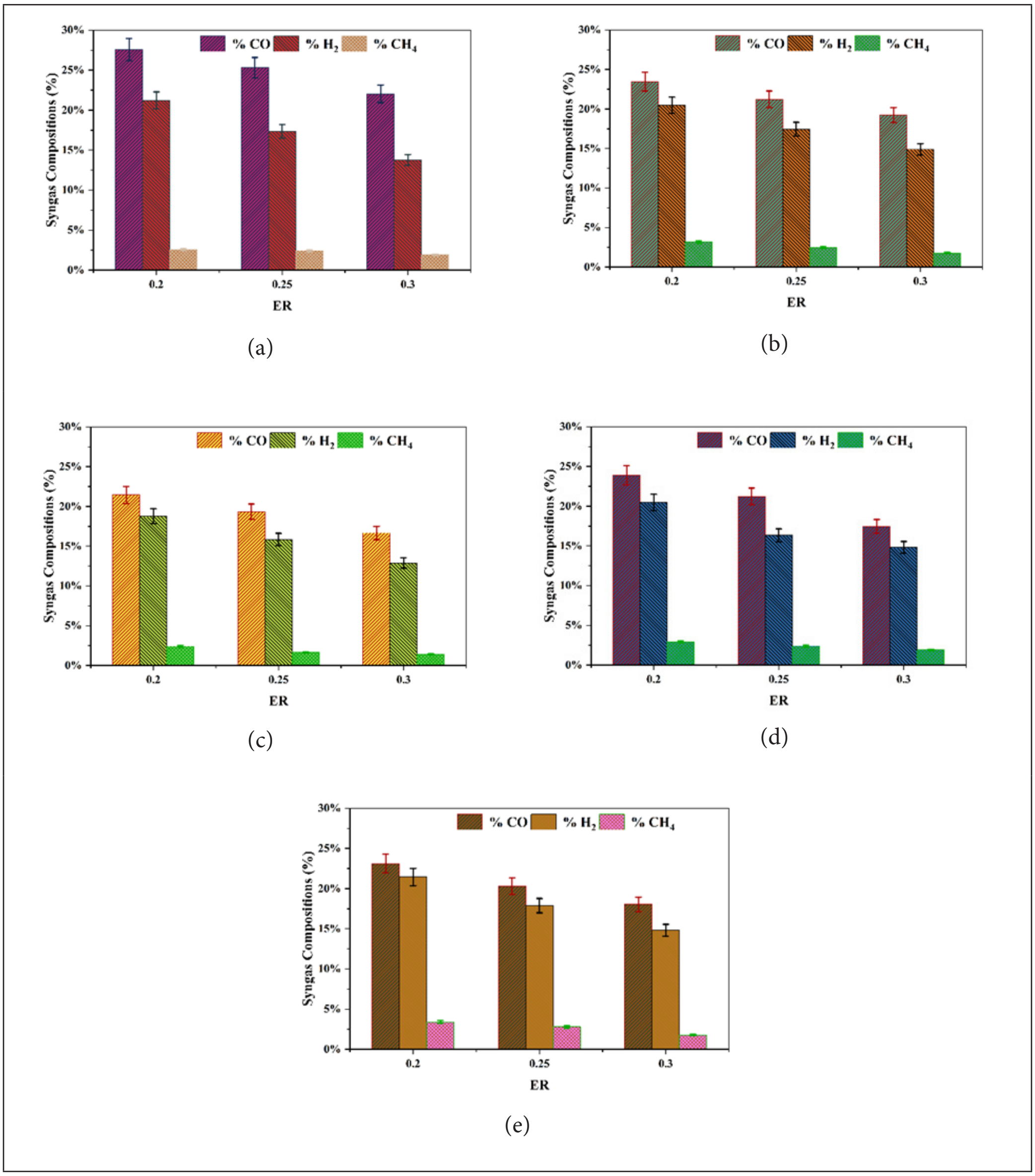


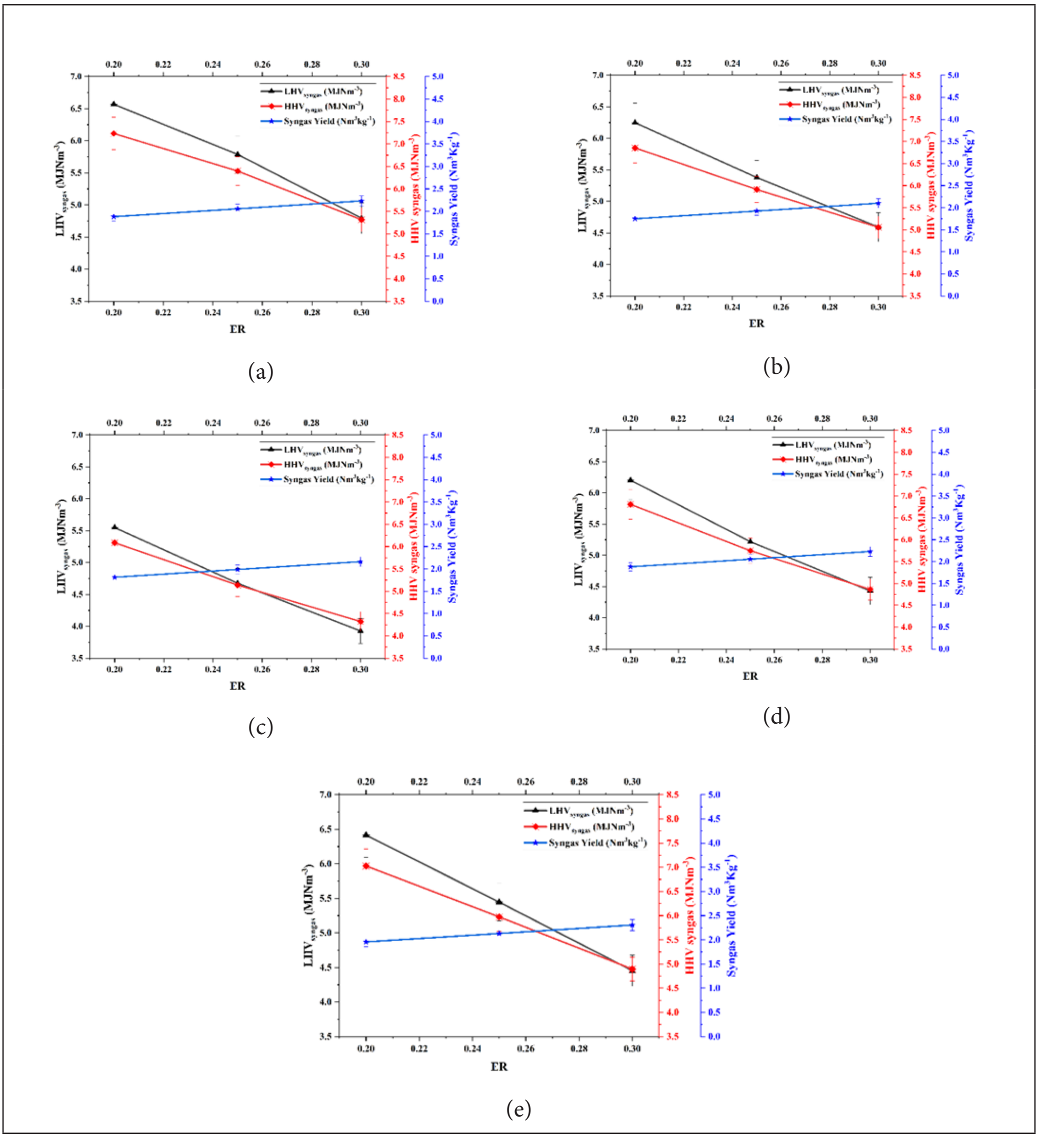
Figure 7. Syngas compositions comparison among different biomass feedstocks at three different ER; (a) Sawdust; (b) Wheat Straw; (c) Rice Husk; (d) Corn Stalk; (e) Spent Tea Waste

methane production (Guo et al., 2014). Jamin et al. (2020a) investigated the influence of equivalence ratio between 0.21 and 0.37 on raw and torrefied wood waste in a fluidised bed gasifier and concluded that with the increasing equivalence ratio, the contents of carbon monoxide, hydrogen and methane decreases with the increasing air supply, it matches with the present trends on CO, H_2 and CH_4 compositional analysis in the syngas. In the case of biomass feedstocks, spent tea waste produces a higher amount of hydrogen gas as compared to other feedstocks due to more hydrogen being present in it. Higher carbon monoxide is produced in the case of sawdust due to the higher carbon content in it. The absence of a peak in syngas composition indicates stable gasification behaviour and efficient biomass conversion throughout the investigated ER range.

Effect of ER on HHV, LHV of Syngas, and Syngas Yield

Syngas yield mainly depends on the equivalence ratio, i.e., fuel and air feeding rate. Syngas yield was determined using Equation 5. It was observed from Figure 8 (a-e) that with the increase in ER, syngas yield increases. Syngas yield was noticed at three equivalence ratios (0.20, 0.25, 0.30). The highest syngas yields were observed of 2.31, 2.23, and 2.23 Nm^3kg^{-1} at ER of 0.3 in spent tea waste, sawdust and corn stalk, separately, in comparison with other feedstocks, i.e., rice husk and wheat straw, which were calculated as 2.16 and 2.10 Nm^3kg^{-1}, respectively. Conversely, lower and higher heating values of syngas primarily depend on the concentration of combustible gases, including carbon monoxide, hydrogen and methane present in it. These heating values were calculated by using Equation 3 and 4. It can be seen from Figure 8 (a-e) that with the increase in the ER from 0.2 to 0.3, the LHV and HHV of syngas decreased in all five biomass feedstocks. Highest LHV and HHV's of syngas were noticed in sawdust feedstock as 6.57 and 7.23 $MJNm^{-3}$, respectively at ER of 0.2 followed by spent tea waste, wheat straw, corn stalk, and then rice husk with the order of 6.42>6.25>6.20>5.55 $MJNm^{-3}$ for lower heating of syngas and 7.03>6.85>6.81>6.09 $MJNm^{-3}$ for higher heating value of syngas.

Syngas yield trends were discussed in the results section, which demonstrated that by increasing ER results, more air is injected into the reactor, resulting in an increase in the syngas production. The equivalence ratio plays a key role in biomass gasification (Sikarwar et al., 2017). The oxidation rates are enhanced by optimising the equivalence ratio. Increase in ER favouring high syngas yield due to increased combustion by producing more heat, resulting in more combustible gases involved in combustion reaction (Liu et al., 2018). As the gas heating values were evaluated based on the concentration of gases, first LHV increases at a higher rate due to stronger combustion reactions in the gasifier, which leads to a higher temperature that results in more generation of H_2 and CO by pyrolysis of biomass and tar decomposition. However, high ER results in the decrement of combustible gases and increment of non-combustible gases such as CO_2 and N_2, which decreases the lower heating value of the syngas as discussed by (Guo et al., 2014; Hendriyana, 2020; Mohammed et al., 2011; Upadhyay et al., 2019). Similar trends were observed in the case of higher heating value of syngas, which shows that at an ER of 0.2, sawdust found highest lower heating value of syngas, which is consistent with the findings of (Susastriawan et al., 2019a).



(a)

(b)

(c)

(d)

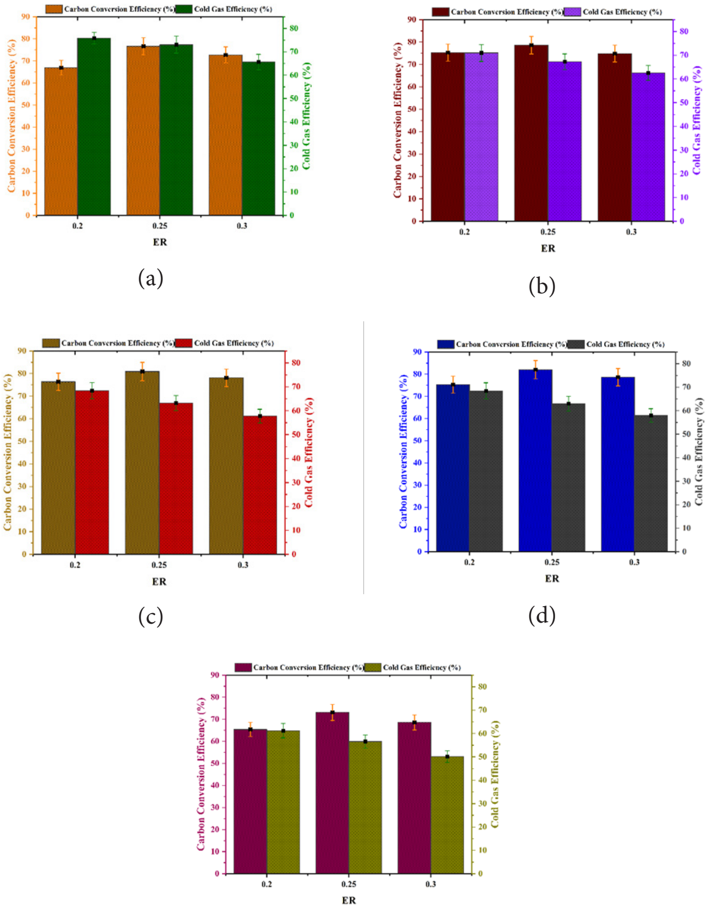
(e)

Figure 8. Comparison of LHV and HHV of syngas and Syngas yield among different biomass feedstocks at three different ER; (a) Sawdust; (b) Wheat Straw; (c) Rice Husk; (d) Corn Stalk; (e) Spent Tea Waste

Maximum HHV of syngas obtained at ER 0.2 indicates that the highest carbon monoxide and hydrogen production occurs at lower ER. By increasing the value of ER beyond 0.2, the HHV of syngas declines due to the higher concentration of nitrogen gas from the air flow rate. Similar trends were observed in previous studies (Jamin et al., 2020a). This contributes to lowering the energy content of the syngas by supplying more nitrogen gas, which dilutes the combustible gases (Lahijani & Zainal, 2011).

Effect of ER on Cold Gas Efficiency (CGE) and Carbon Conversion Efficiency (CCE)

It can be seen from several studies that ER plays a vital role in the determination of gasification performance. Figure 9 (a-e) illustrate the cold gas efficiency and carbon conversion efficiency values at various ER levels. These efficiencies were calculated using Equation 6 and 7, respectively. At ER 0.2, cold gas efficiency increased rapidly and approached a high level of about 75.84% in the case of sawdust in comparison with other biomass feedstocks, which is noted as maximum at 70.96%, 68.45%, 68.39% and 61.22% in the case of wheat straw, corn stalk, rice husk and spent tea waste. And began to decrease with further increase in ER. Meanwhile, with the increase in ER from 0.2 to 0.25,



(a) (b) (c) (d) (e)

Figure 9. Comparison of Cold gas efficiency and Carbon conversion efficiency among various biomass feedstocks at three different ER; (a) Sawdust; (b) Wheat Straw; (c) Rice Husk; (d) Corn Stalk; (e) Spent Tea Waste

carbon conversion efficiency increases in each type of biomass feedstock, and the highest value is measured at ER of 0.25 in the case of corn stalk, which is 82.0%. All other biomass feedstocks followed the same trend as 81.0, 78.6, 76.6 and 73.1 % in rice husk, wheat straw, sawdust and spent tea waste, respectively. As ER continues to increase, carbon conversion efficiency declines.

To examine the effect of ER on energy and mass conversion, variations in cold gas efficiency and carbon conversion efficiency were analysed. An increase in the equivalence ratio (ER) promotes oxidation reactions, resulting in reduced CO and H_2 concentrations and, consequently, a decrease in the heating value of the syngas. As a result, the cold gas efficiency started to decline when ER exceeded 0.2, indicating a reduction in the overall energy conversion of biomass (Hendriyana, 2020; Karmakar et al., 2013; Zheng et al., 2016). Since the CGE of the fluidised bed gasification reactor fed by sawdust, wheat straw, rice husk, corn stalk and spent tea waste is still higher than 60 % at ER 0.2, it can be concluded that the FBG reactor is ideal for sawdust, wheat straw, rice husk, corn stalk and spent tea waste. In the earlier study, Yoon et al. (2012) reported a CGE ranging from 50% to 70% for rice husk gasification, while Wander et al. (2004) attained a CGE of 67.67% for sawdust gasification, which falls within the range of the present study. In contrast, carbon conversion efficiency exhibits a slight decrease beyond a certain equivalence ratio. At ER = 0.2, the limited oxygen supply favours reactions such as the Boudouard reaction (R3) and the water–gas reaction (R2), resulting in higher CO and H_2 concentrations and a correspondingly higher heating value of the syngas. However, the limited char oxidation at this ER leads to slightly lower carbon conversion efficiency, which may cause incomplete carbon conversion. At ER = 0.25, the oxygen supply is balanced, providing stable ignition and sufficient char oxidation, thereby increasing the carbon conversion efficiency and improving overall gasification performance. At ER = 0.3, a slight decrease in carbon conversion efficiency is observed, which can be attributed to the increased air flow rate. The higher flow raises the superficial gas velocity and reduces the residence time available for char–gas reactions, resulting in a marginal decline in carbon conversion efficiency at higher oxygen levels, as reported in the literature (Gurusamy, 2016; Khezri et al., 2016; Maitlo et al., 2022).

Wang et al. (2025) reported cold gas efficiency values exceeding 60% under optimised gasification conditions. Similarly, Susastriawan and Saptoadi (2023) observed peak cold gas efficiency in a downdraft gasifier within an equivalence ratio range of 0.20-0.25, with the maximum value occurring at an equivalence ratio of 0.20. In addition, system-level reviews by (Rahmah & Nurhilal, 2025; Wang et al., 2025) indicate that optimal gasification performance, characterised by high cold gas efficiency and carbon conversion efficiency, is generally achieved at equivalence ratios in the low-to-mid 0.2 range for biomass gasifiers.

These findings confirm that the performance metrics obtained in the present study fall within the typical range reported for optimised biomass gasification systems in recent literature.

Temperature Profile of the Gasification Process

Figure 10 illustrates the average temperature profile with respect to time at different ER values of 0.2, 0.25, and 0.3. For all biomass wastes, the reactor temperature rises rapidly during the initial heating stage and reaches a quasi-steady state after 40-50 minutes under external heating conditions, confirming stable operation. An increase in ER leads to higher peak temperatures, with average steady-state values of approximately 850 °C, 940 °C, and 1000 °C for ER values of 0.2, 0.25, and 0.3, respectively. The observed syngas composition trends reflect the effect of ER, with temperature variations being a naturally coupled outcome in air-blown fluidised bed gasification. This behaviour is attributed to the increased availability of oxygen at higher ER, which enhances exothermic oxidation reactions and internal heat generation, a trend generally consistent with previous studies (Jamin et al., 2020b; Sasujit et al., 2022; Valin et al., 2020). At longer operating times, a slight temperature decline is observed, likely due to heat losses and gradual changes in

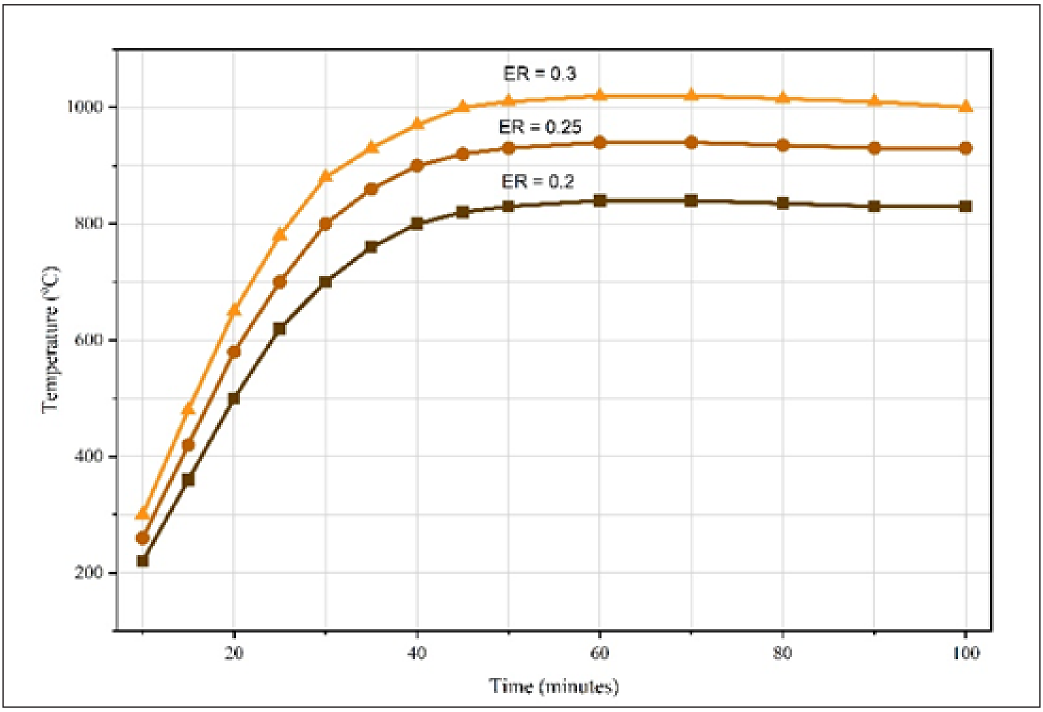


Figure 10. Average temperature profile inside the gasifier at three different ER

char reactivity. Overall, the findings of this study demonstrate good thermal behaviour of the system, consistent with the expected temperature profile during gasification.

CONCLUSION

The gasification performance of five biomass feedstocks was systematically investigated under varying equivalence ratios (ERs) with emphasis on syngas composition, heating value, syngas yield, cold gas efficiency (CGE), and carbon conversion efficiency (CCE). Among the tested feedstocks, sawdust produced the highest CO concentration of 27.56% at an optimum ER of 0.2, while the maximum H_2 content of 21.45% was obtained from spent tea waste. The highest lower and higher heating values of syngas, 6.57 and 7.23 MJ Nm^{-3}, respectively, were also observed for sawdust at an ER of 0.2. Spent tea waste yielded the maximum syngas production of 2.31 Nm^3kg^{-1} at an ER of 0.3. The highest CGE of 75.84% was achieved with sawdust at an ER of 0.2, and CGE values above 60% for all feedstocks at this ER indicate the operational feasibility of the reactor. Among the evaluated biomasses, corn stalk exhibited the highest carbon conversion efficiency of 82.0% at an ER of 0.25, demonstrating its strong gasification potential.

In conclusion, the indigenised pilot-scale fluidised bed gasifier demonstrated stable operation and efficient gasification across various biomass feedstocks. These findings highlight the potential of locally designed fluidised bed gasifiers for sustainable heat and power generation and provide a foundation for further scale-up and optimisation studies.

Future studies should focus on the effects of particle size distribution and blended solid fuels on gasification behaviour. Furthermore, detailed techno-economic analysis (TEA) and mass-energy balance modelling are essential for multiscale system optimisation and for facilitating demand-driven implementation of the proposed technology.

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CONFLICTS OF INTEREST

The authors declare that they have no competing interests.

AUTHORS' CONTRIBUTION

Shahbaz Hussain: formulation, investigation, methodology, visualisation, writing, original draft preparation. Prof. Dr Abdul Nasir: formal analysis, methodology, validation, and reviewing. Dr Ch. Arslan: formal analysis, reviewing. Dr. Shakeel Ahmad Anjum: formal analysis. Dr. Sibel Irmak: formal analysis-reviewing.

ABBREVIATIONS

FBG : Fluidised bed sasifier
SD : Sawdust
WS : Wheat straw
RH : Rice husk
CS : Corn stalk
STW : Spent tea waste
RS : Rice straw
CCE : Carbon conversion efficiency
CGE : Cold gas efficiency
LHV : Lower heating value
NO_x : Nitrogen oxides
SO_x : Sulfur oxides
CO_2 : Carbon dioxide
CH_4 : Methane
CO : Carbon monoxide
N_2 : Nitrogen
H_2 : Hydrogen
WtE : Waste-to-Energy
MSW : Municipal solid waste
ER : Equivalence ratio
UAF : University of agriculture, faisalabad
ABE : Agricultural and biological engineering
PA : Pennsylvania
ASTM : American society for testing and materials
LAP : Laboratory analytical procedure
WGS : Water-gas shift
NTP : Normal temperature and pressure

TEA	:	Techno-economic analysis
HEC	:	Higher education commission
NCPC	:	National cleaner production centre

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