



Experimental investigation on hydrogen-rich syngas production via gasification of common wood pellet in Bangladesh: Optimization, mathematical modeling, and techno-econo-environmental feasibility studies

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Abstract

Since hydrogen produces no emissions, there is increasing interest in its production throughout the world as the need for clean and sustainable energy grows. Bangladesh has an abundance of biomass, particularly wood pellets, which presents a huge opportunity for gasification to produce hydrogen. Gasification of mahogany (*Swietenia mahagoni*-SM) and mango (*Mangifera indica*-MI) wood is performed in a downdraft gasifier to evaluate the impact of particle size, equivalence ratio, and temperature on hydrogen gas composition and gasifier performance. Under the optimal conditions determined by central composite design-response surface methodology (CCD-RSM) optimization, gasification of SM and MI wood can greatly increase hydrogen yield and cold gas efficiency, offering a workable, environmentally friendly, and long-term solution to Bangladesh's energy shortage and pollution problems. Through RSM analysis the best operating conditions for gasification of SM wood include a feed size of 22.5 mm, equivalence ratio of 0.34, and operating temperature of 1176 K, where a total yield of hydrogen 11.2% was obtained. In the case of MI wood gasification, the optimum condition was found at feed size 22.5 mm, equivalence ratio 0.34, and operating temperature of 1132.47 K, where a total yield of hydrogen 12.85% was obtained. The economic study provides an LCOE of 0.1116 \$/kWh, the project payback period is determined to be 10.7 years. By reusing wood waste from nearby sawmills, this study helps to manage waste sustainably by lowering pollution levels and deforestation. It also highlights wider sustainability effects by assisting international initiatives to fight climate change and advance energy independence.

Keywords Hydrogen · Gasification · Wood pellet · Response Surface Methodology · Optimization

1 Introduction

The generation of low-emission hydrogen can improve the sustainability of sectors that are difficult to decarbonize, such as commercial and domestic heating. With the increase in industrialization, quality of life, and population, the global energy demand experiences a significant increase year by year. This upward trend in energy demand is directly correlated with the rise in carbon dioxide

emissions [1]. The objective is to decrease society's reliance on fossil fuels, which now serve as the primary source of energy. In the context of global energy security, renewable energy has made significant strides in garnering support and attention. Renewable energy resources (REs) accounted for approximately 29.8% of global energy consumption in 2022 [2]. The sources of renewable energy encompass biomass energy, solar energy, wind energy, and hydropower. Modern machine learning (ML) techniques can optimize renewable energy systems, but their "black box" nature limits transparency and accountability, which explainable AI aims to address, enhancing system performance and efficacy while requiring further research to overcome challenges related to transparency, accountability, and fairness [3]. In the present era, biomass is widely accessible on a global scale, with the majority originating

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from crops [4]. Biomass can be transformed into energy using many thermochemical methods, including gasification, pyrolysis, torrefaction, and liquefaction [5]. Biomass gasification refers to the process of converting biomass into a gaseous fuel through a thermochemical reaction [6]. In gasification, biomass is partially combusted to produce syngas [7]. There has been much research on hydrogen and it is recognized as a practical mainstream fuel alternative [8]. The global energy sector has experienced a significant increase in geopolitical influence in recent years, which has hurt the expansion of all energy sectors involved in the "green transition," including hydrogen energy [9]. World leaders made the momentous decision to create new financial tools and a special fund to help developing nations respond to losses and destruction brought on by climate change during the Conference of the Parties, or COP 27 [10]. Hydrogen is an appealing alternative for lowering greenhouse gas emissions and battling climate change as it doesn't release any hazardous emissions when burned like fossil fuels do [11]. Combining hydrogen with diesel synthesis gas improved brake thermal efficiency and greatly decreased emissions of smoke, hydrocarbons, and carbon monoxide [12]. The combustion of a gasoline engine running on ethanol-blended gasoline (E30) with hydrogen had been improved, and CO and HC emissions were decreased, while NO_x emissions rose [13]. When combined with natural gas at a ratio of up to 5–30%, hydrogen helps internal combustion engines operate more efficiently and produce less emissions [14]. Because hydrogen can store and transport clean energy, it facilitates the integration of various industries into a unified energy market by converting electric energy into chemical energy [15]. Hydrogen is crucial for transitioning to a zero-carbon economy, with green hydrogen potentially replacing fossil fuels in various sectors and enhancing energy security [16]. The expenses associated with hydrogen energy and fuel cell applications, including fuel cell electric automobiles (FCEVs) and fuel cell power plants, have been rapidly declining as a result of the consistent advancement of technology and supply chains in the field of hydrogen energy [17]. The application of hydrogen in maritime transportation is still in its infancy because of obstacles such as restricted cabin areas, storage issues, inadequate port infrastructure, exorbitant expenses, and the requirement for more regulations and rules [18]. Population growth and rapid development have resulted in tremendous waste output, posing serious ecological and socioeconomic concerns in Bangladesh [19]. Bangladesh's daily solid waste generation is expected to reach 47,000 tons by 2025 [20]. Around 2.2% of the total solid waste generated in Bangladesh is wood waste [21]. Municipal Solid waste (MSW) management is a serious issue in Bangladesh since the disposal of waste takes up a lot of space [22]. Wood waste and byproducts

from wood-based industrial operations can be gasified to produce syngas.

The gasification process is influenced by several factors, including the chemical and physical properties of biomass, the gasifier's design, and the operational parameters, such as temperature, equivalency ratio, and feedstock size [23]. Presently, multiple commercial gasifier designs, including updraft, downdraft, and fluidized-bed gasifiers, have been created. The downdraft gasifier is very sustainable for combined heat and power generation due to its low tar and particle content in the syngas it produces [24]. A multitude of studies has been conducted in the realm of biomass gasification to evaluate the influence of several operational variables, such as temperature, residence time, steam-to-biomass ratio, particle size, and biomass content, on the efficiency of the gasification process. The summarized literature survey relevant to the research work is presented in Table 1.

To the best of the author's knowledge, not much comprehensive research has been done to examine whether it is feasible to evaluate the techno-economic-environmental factors and optimize process parameters to gasify SM and MI wood using a fixed-bed downdraft reactor while maximizing hydrogen yield and cold gas efficiency. Conducting techno-economic feasibility studies is essential in assessing a project's commercial viability as it expands. As far as the authors are aware, no literature has been located covering the techno-economic feasibility analysis of the gasification project. Moreover, a careful review of the relevant literature reveals that no previous studies have investigated how process factors affect characterization, optimization, performance analysis, and production as a whole. Bangladesh's fast expansion and expanding population have produced a huge amount of waste, raising major ecological and socioeconomic issues. Wood waste accounts for a sizable portion of that waste. Hydrogen, a promising substitute that reduces greenhouse gas emissions without producing dangerous pollutants, may be used to address these waste management issues and fight climate change at the same time. Bangladesh's fast expansion and expanding population have produced a huge amount of waste, raising major ecological and socioeconomic issues. Wood waste accounts for a sizable portion of that waste. Hydrogen, a promising substitute that reduces greenhouse gas emissions without producing dangerous pollutants, may be used to address these waste management issues and fight climate change at the same time. The current study investigates and resolves the identified weaknesses and vulnerabilities. Hence, the research project has expanded to include the assessment of how particle size, equivalence ratio, and temperature impact the gasification output. This evaluation particularly focuses on the gas composition yield (CO, CH₄, and H₂) and the overall efficiency of the gasification process. Additionally, to enhance the product yield, the utilization of response surface

Table 1 Summary of research work on biomass gasification process

Researcher (s)	Study Focus	Feedstock and Size	Key Findings
Inayat et al. [25]	Impact of biomass mixing ratio and particle size on syngas quality and co-gasification efficiency	Biomass, particle sizes 5–10 mm and 25–50 mm	Smaller particles (5–10 mm) improved syngas quality compared to larger particles (25–50 mm). Syngas energy content: H ₂ increased from 3.96 to 5.59 MJ/Nm ³ , CO from 9.76% to 10.91%, and CH ₄ from 17.05% to 25.60%. CGE increased from 58.63% to 64.81%
Yin et al. [26]	Effect of particle size on gasification performance in a downdraft fixed bed system	Peach tree pruning's, five size fractions < 1 cm to 2 cm	Smaller particle sizes led to higher concentrations of H ₂ (16.09%) and CO ₂ (14.36%). Optimal particle size: 1–2 cm for peach tree pruning
Patel et al. [27]	Effect of lignite particle sizes on downdraft gasifier performance	Lignite, particle sizes 13–31 mm	Particle sizes from 13 to 25 mm increased gas content and calorific value, but sizes from 25 to 31 mm did not have the same effect
Hernández et al. [28]	Impact of particle size and residence time in an entrained flow gasifier	Grapevine pruning, sawdust wastes, grape marc; various sizes	Smaller particle sizes enhanced gasification performance for all three biomass sources
Yahaya et al. [29]	Air gasification of corn stover (CS) and palm kernel shell (PKS) using varying particle sizes and temperatures	CS and PKS, particle sizes 1–3 mm, 4–7 mm, 8–11 mm	Smaller particle sizes and higher temperatures improved gas composition. For CS: energy content 4.01–5.39 MJ/Nm ³ , gas yield 1.50–1.90 Nm ³ /kg, CCE 52.2–75.9%, CGE 30.9–56.4%. For PKS: energy content 3.82–5.09 MJ/Nm ³ , gas yield 1.48–1.92 Nm ³ /kg, CCE 59–81.5%, CGE 33–57.1%
Zainal et al. [30]	Utilization of wood chips and charcoal in a downdraft gasifier	Wood chips and charcoal, of various sizes	Calorific value increased with equivalence ratio, peaking at 5.34 MJ/Nm ³ at an equivalence ratio of 0.388. Incomplete carbon conversion noted
Tinaut et al. [31]	A one-dimensional model of the biomass gasification process	Wood, various sizes	Model tested with different wood sizes and air superficial velocities
Sheth and Babu [32]	Air-to-fuel ratio and equivalence ratio in a gasifier	Biomass, air-to-fuel ratio: 1.37–1.64 Nm ³ /kg	Optimal air-to-fuel ratio: 1.44–1.47 Nm ³ /kg; equivalence ratio: 0.262–0.314. Produced gas calorific value: ~ 5 MJ/m ³
Olgun et al. [33]	Portable fixed bed downdraft gasifier using agricultural and forestry waste	Agricultural and forestry waste, of various sizes	Developed and tested the system
Branch et al. [34]	Lab-scale downdraft gasifier performance test	Biomass, various sizes	Produced combustible syngas
Htut et al. [35]	Pilot-scale downdraft gasifier performance evaluation	Biomass, various sizes	Evaluated biomass consumption rate, LHV, energy efficiency, and SGR
Olayanju et al. [7]	Analysis of syngas using infrared and electrochemical sensors	Analysis of syngas using infrared and electrochemical sensors	Developed downdraft gasifier
Narendrabhai et al. [36]	Lab-scale downdraft gasifier performance with different woodblock sizes	Wood blocks, of various sizes	Achieved steady flame and clean combustible syngas
Chawdhury and Mahkamov [37]	6 kW downdraft gasifier performance test	Wood chips (3.1 kg/h) and wood pellets (2.9 kg/h)	Thermal efficiency: 90.1–92.4%; feedstock rate: 3.1 kg/h for wood chips, 2.9 kg/h for wood pellets
Susastriawan et al. [38]	Design improvements for downdraft gasifiers	Biomass, various sizes	Improved feeding, multi-stage, preheating, and recirculating systems

Table 1 (continued)

Researcher (s)	Study Focus	Feedstock and Size	Key Findings
Akhtor et al. [39]	Downdraft gasifier performance test	Wood chunks (1.25 kg/h) and wood shavings (2.1 kg/h)	Feedstock conversion rate: 1.25 kg/h for wood chunks, 2.1 kg/h for wood shavings. Design based on Imbert and stratified models
Mendonça et al. [40]	Imbert-type downdraft gasifier with clean-up mechanism	Biomass, various sizes	Combustion zone temperature: 1200 °C

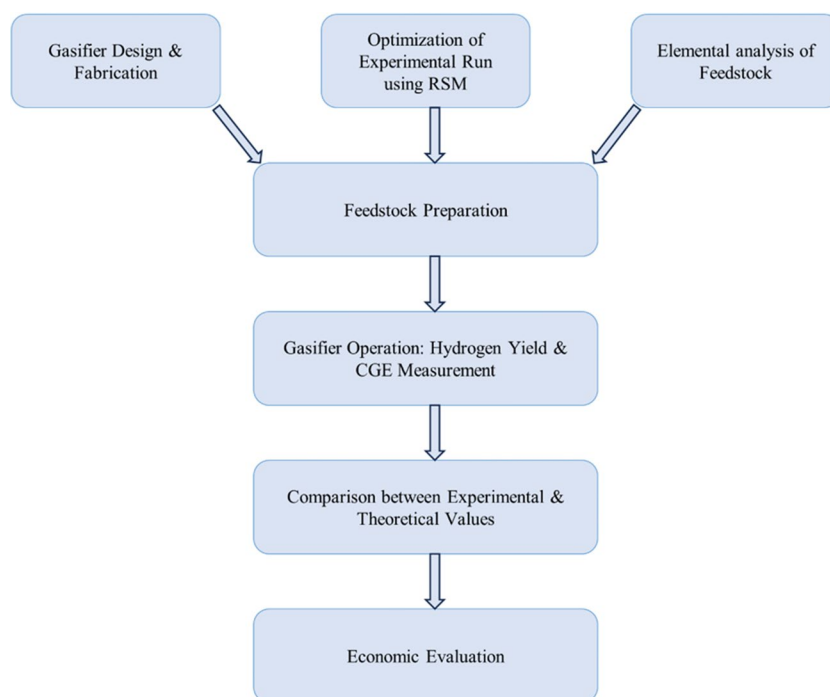
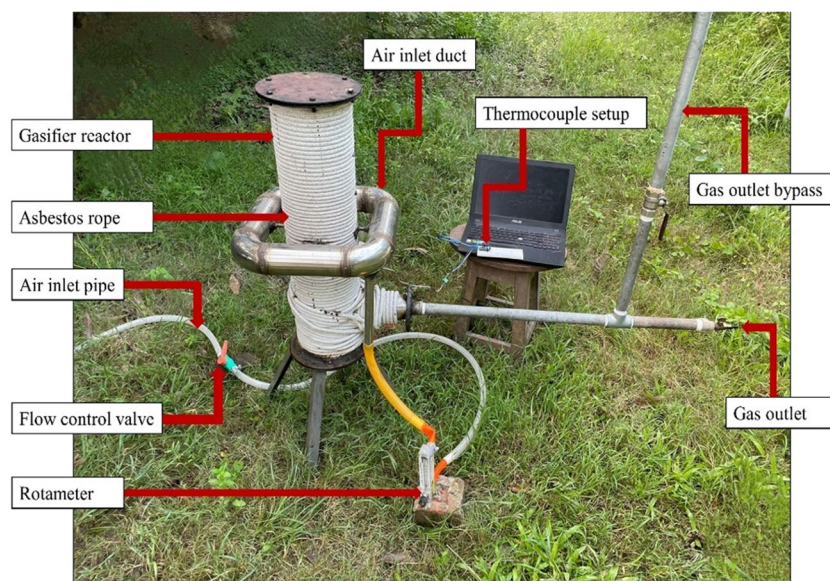
methodology (RSM) and analysis of variance (ANOVA) modeling is employed to assess the influence of various process factors on cold gas efficiency and hydrogen output. This study aims to enhance the production of hydrogen and improve the efficiency of the cold gas by utilizing RSM. This will be achieved by considering various input parameters such as particle size, equivalence ratio, and operating temperature. The discrepancy between anticipated and actual values is represented by mathematical models of hydrogen production and the efficiency of cold gas. An evaluation of the rationality of developing a gasification plant also involved an analysis of its economic feasibility.

2 Materials and method

Figure 1 provides a quick overview of the research methodology. It shows the gasifier project process beginning with three parallel activities: gasifier design and manufacturing, optimization using modeling and Response Surface Methodology (RSM), and elemental analysis of the feedstock. The feedstock is prepared following the optimal RSM design after these parallel procedures. The gasifier is then run to measure the cold gas efficiency (CGE) and hydrogen output. Next, a comparison is made between the measured and theoretical values. Ultimately, the entire process is evaluated economically.

2.1 Feed material preparation and experimental procedure

The acquisition, processing, and analysis of feed materials is a crucial stage in the gasification process. The raw material was gathered, purified, dried in the sun, and then subjected to an oven-drying process at a temperature of 105 °C for a duration of four hours, to decrease the amount of moisture present. The effectiveness of the feed ingredients was assessed using proximate, ultimate, and TG/DTG tests. Fixed bed downdraft gasifiers have demonstrated superior performance compared to other types of gasifiers. Figure 2 depicts the configuration of the downdraft gasifier used in the experiment. The gasifier is constructed from stainless steel and is thermally insulated with asbestos rope. A K-type temperature sensor was inserted into a drilled hole to monitor the temperature in the combustion zone of the gasifier. A rotameter was employed to regulate and oversee the airflow within the gasifier. Throughout each iteration of the experiment, the resulting syngas were examined using an infrared gas analyzer. This study involved doing both ultimate and proximal analysis on two distinct wood types: MI and SM. The ultimate examination yielded the precise elemental makeup of the wood samples, including the quantity of carbon, hydrogen, nitrogen, sulfur, and oxygen. Conversely,

Fig. 1 Current flow of research work**Fig. 2** Complete experimental setup

the proximate analysis facilitated the determination of the moisture, volatile matter, fixed carbon, and ash content in the wood samples. After conducting these studies, thermogravimetric (TG) and derivative thermogravimetric (DTG) analyses were carried out on the wood samples. The investigations yielded useful insights into the thermal stability and breakdown properties of the wood. The thermogravimetric (TG) study demonstrated the correlation between the temperature and the reduction in mass of the wood samples, whereas the differential thermogravimetric (DTG) analysis quantified the rate at which mass was lost. Ultimately, the

syngas generated from the wood samples were examined utilizing a gas analyzer. This instrument facilitated the quantification of the quantities of several constituents in the syngas, encompassing hydrogen, carbon monoxide, carbon dioxide, and methane. The investigation yielded valuable insights regarding the gasification process and the quality of the syngas produced.

Cold gas efficiency (CGE) is a way of measuring the energy efficiency of the syngas produced by the gasifier. It's calculated using the lower heating value (LHV) of the produced gas and the lower heating value (LHV) of the input

fuel. The cold gas efficiency was determined using Eq. 1 [37].

$$\eta_{CG} = \frac{E_{syngas}}{E_{biomass}} \quad (1)$$

$$E_{syngas} = AFR \left(\frac{m^3}{h} \right) \times HV_{pg} \left(\frac{MJ}{m^3} \right) \quad (2)$$

$$HV_{pg} = \frac{(x_1 \cdot HV)_{CO} + (x_2 \cdot HV)_{H_2} + (x_3 \cdot HV)_{CH_4}}{100} \quad (3)$$

$$E_{biomass} = CR \left(\frac{kg}{h} \right) \times HV_b \left(\frac{MJ}{kg} \right) \quad (4)$$

where, AFR = Air Flow Rate, HV_{pg} = heating value of produced gas, x_1 , x_2 , and x_3 are the percentage of combustible gas CO, H_2 , and CH_4 in producer gas, CR = biomass consumption rate and HV_b = heating values of biomass.

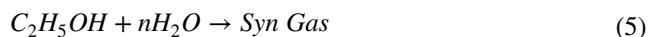
2.2 Process optimization and mathematical model for cold gas efficiency and hydrogen yield

The central composite design (CCD) of the response surface methodology (RSM) is specifically designed to capture quadratic effects and interactions among input variables. This technique consists of a central point, typically reflecting the mean values of the input variables, a series of star points evenly distributed about the central point, and a final point that represents the output of the procedure. The star points have the function of determining the most favorable input variable settings and assessing the curvature of the response surface. The CCD also demonstrates greater efficiency in reducing the number of experiments needed for model development and determining optimal input configurations. Additionally, this process involves training and evaluating the model using many subsets of the available data. Every cycle, a subset is designated for validation and the remaining subsets are used to train the model. Unlike hold-out validation, this method uses all of the data available for both validation and training, which results in a more accurate assessment of the model's performance. It is feasible to examine the model's coefficients and do a statistical analysis of the data to ascertain whether interactions exist in the RSM model. A correlation between an input parameter's size and its effect on the response variable can be found in the model by identifying significant interaction terms. A higher F-value signifies a substantial enhancement in model performance resulting from the inclusion of an interaction term, showing a meaningful interaction between input parameters. To optimize the gasification process and increase the yield of hydrogen while enhancing the efficiency of cold gas production,

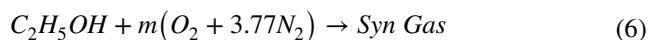
this study used the RSM using the Design Expert software. Particle size, equivalency ratio, and operating temperature were among the critical input process variables that were mainly investigated. As a regression technique, we used a traditional RSM design, namely the CCD, to evaluate the impact of these process factors on the gasifier's performance. In this investigation, 40 trial runs in all, 20 runs for each type of wood are used. The experiment's design matrices are what are known as these runs. The results are included in Table 2 and Table 3. To examine the collected experimental data, we utilized the Analysis of Variance (ANOVA) technique with the aid of the Design Expert program. This thorough approach included experimental design, data analysis, constructing quadratic models, and generating three-dimensional (3D) response surface graphs using the input process parameters.

2.3 Method of hydrogen production

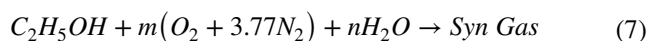
An environmentally friendly and carbon-neutral fuel source for the creation of hydrogen is bioethanol. Various research compares the ethanol reforming methods, such as autothermal, partial oxidation, and steam reforming, to determine how the catalyst's physicochemical characteristics and experimental parameters affect the amount of hydrogen produced. Interestingly, at 400 °C, all three methods achieve 75% hydrogen selectivity [41]. The ethanol-steam mixture in the steam reforming system is catalytically transformed into hydrogen, carbon monoxide, carbon dioxide, and methane (Eq. 5) [42].



The incomplete oxidation of the feed is what the partial system depends on. The fuel supply undergoes a sub-stoichiometric oxidation as a result of the partial oxidation process (Eq. 6) [42], which fractionates the feed into smaller molecules and produces heat.



The auto-thermal forming process (Eq. 7) [42] is the combination of steam reforming and partial oxidation process. The heat produced by the partial oxidation exothermic reaction helps to perform the endothermic steam reforming reaction. Since auto-thermal forming processes are considered to be thermally self-sustaining, they neither produce nor use thermal energy from outside sources.



When it comes to long-term sustainability and supplying the growing need for energy, photocatalysis-derived hydrogen from water splitting is thought to be the most

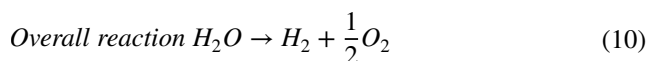
Table 2 Experimental design matrix and results for MI wood

Obs. No	A: Feedstock size (mm)	B: Equivalence ratio	C: Operating temp. (K)	Hydrogen yield (wt. %)	Cold gas efficiency (%)
1	22.5	0.146484	1123	13.5	29.17608
2	22.5	0.195313	1127	13.2	38.98929
3	22.5	0.244141	1132	12.8	50.69478
4	22.5	0.292969	1141	12.7	64.81834
5	22.5	0.341797	1148	12.1	75.66249
6	32.5	0.146484	1105	13.3	27.80547
7	32.5	0.195313	1113	13.1	37.46799
8	32.5	0.244141	1125	12.9	48.01576
9	32.5	0.292969	1131	12.6	61.65309
10	32.5	0.341797	1134	12	72.56792
11	42.5	0.146484	1100	11.9	26.28417
12	42.5	0.195313	1104	11.6	35.45612
13	42.5	0.244141	1107	11.2	47.70262
14	42.5	0.292969	1113	11.1	60.51538
15	42.5	0.341797	1116	10.8	71.75204
16	55	0.146484	1088	11.5	25.57898
17	55	0.195313	1096	11	34.68198
18	55	0.244141	1118	10.6	43.88633
19	55	0.292969	1122	10.2	54.1301
20	55	0.341797	1125	9	63.13351

Table 3 Experimental design matrix and results for SM wood

Obs. No	A: Feedstock size (mm)	B: Equivalence ratio	C: Operating temp. (K)	Hydrogen yield (wt. %)	Cold gas efficiency (%)
1	22.5	0.159439	1152	12.2	33.31268
2	22.5	0.204993	1160	11.9	43.1858
3	22.5	0.250547	1168	11.7	54.44747
4	22.5	0.296101	1172	11.4	68.71737
5	22.5	0.341655	1176	11.2	79.20936
6	32.5	0.159439	1140	11.8	31.3605
7	32.5	0.204993	1151	11.6	41.38334
8	32.5	0.250547	1164	11.3	50.70043
9	32.5	0.296101	1169	11	63.91873
10	32.5	0.341655	1174	10.9	76.16937
11	42.5	0.159439	1124	11.1	29.89998
12	42.5	0.204993	1132	10.8	38.64832
13	42.5	0.250547	1154	10.6	50.31173
14	42.5	0.296101	1160	10.2	63.45512
15	42.5	0.341655	1165	9.9	75.26912
16	55	0.159439	1126	10	27.50028
17	55	0.204993	1141	9.6	38.14536
18	55	0.250547	1145	9.1	46.57905
19	55	0.296101	1154	8.8	56.45575
20	55	0.341655	1162	8.6	71.43488

practical hydrogen generation technology [43]. Photocatalysts supported by metal and carbon exhibit great potential for producing hydrogen from water using solar energy. The water split reactions are (Eqs. 8, 9 and 10) [44]



In the traditional gasification process, air is used as an oxidizing agent, but this in turn leads to a significantly lesser conversion from biomass to hydrogen. The use of O_2 as an oxidizing agent results in higher hydrogen composition [45]. To attain a balance between air and oxygen gasification, steam gasification was necessary during the gasification process. Steam gasification had the same hydrogen content (40%) as oxygen gasification [46]. Catalysts were used in gasification because they could reduce the activation energy required for reactions and increase the efficiency of carbon conversion for higher gas outcomes. This allowed for an increase in steam reforming

reactions and tar cracking, as well as an increase in the speed at which H_2 was produced [46].

2.4 Economic indicators

Economic analysis primarily depends on capital expenses and cash flow assessment to ascertain the necessary investment and syngas production costs [47, 48]. Kim and Parker [49], suggest that the most efficient means of evaluating a process's scalability is through economic analysis. The total life-cycle cost (TLCC) can be expressed as a combination of the initial investment cost (INV_{cst}) and the operation and maintenance costs ($O\&M_{cst}$). Eq. 11 was utilized to establish the project's TLCC [50].

$$TLCC = INV_{cst} + \sum_{n=1}^t \frac{O\&M_{cst}}{(1 + \alpha)^n} \quad (11)$$

Considering that the anticipated useful life of the project is 20 years, and the nominal discount rate stands at 10% [50]. The assessment of a project's profitability hinges on the net present value (NPV) of the project. A positive NPV signifies the economic viability of the project, while negative cash flows suggest its infeasibility. The project's net present value (NPV) was calculated using Eq. 12 [50], where L_n stands for the project's net cash flow and r is the yearly real discount rate, both of which may be figured out using Eq. 13 [50].

$$NPV = \sum_{n=0}^y \frac{L_n}{(1 + \alpha_r)^n} = INV_{cst} + \frac{L_1}{(1 + \alpha_r)^1} + \dots + \frac{L_t}{(1 + \alpha_r)^t} \quad (12)$$

$$\alpha_r = \left[\frac{1 + \alpha}{1 + ln_r} \right] \quad (13)$$

The project's nominal discount rate, and inflation rate, ln_r , are both set at 10% and 9.3%, respectively [50]. An essential metric in economic feasibility assessments is the internal rate of return (IRR), employed to gauge the potential profitability of projects. In the context of IRR calculations, the NPV of all cash flows for a specific project is set to zero. It has been determined that for a project to be profitable, the IRR value must equal or exceed the target value. To evaluate the project's IRR, Eq. 14 was applied.

$$IRR = 0 = NPV = \sum_{n=0}^t \frac{L_n}{(1 + IRR)^n} \quad (14)$$

The duration required for a project's initial investment to start generating returns is referred to as the Initial Payback Period (IPBP). During this period, the investment cost for the project remains constant and is equivalent to the $O\&M_{cst}$. The investment payback period (IPBP) for the proposed gasifier plant was calculated using Eq. 15 [51], where TFC is the project's initial total fixed cost, V stands for the plant's

annual total cost (fixed cost + variable cost), and P is the pyrolysis plant's gross revenue.

$$IPBP \text{ (year)} = \frac{TFC}{P - V} \quad (15)$$

The LCOE (Levelized Cost of Electricity), representing the minimal cost of power generation for the project in terms of dollars per kilowatt hour (\$/kWh) when it reaches the break-even point, stands as a vital economic metric for evaluating the project's profitability. Equation 16 [50] was used to determine the projects' LCOE.

$$LCOE = \left[\frac{TLCC}{G_{EP}} \times \frac{\alpha(1 + \alpha)^t}{(1 + \alpha)^t - 1} \right] \quad (16)$$

2.5 Uncertainty analysis

To ascertain the mistakes made in the tests due to the instruments utilized, calibration, accuracy calculations, methods applied in an ambient state, etc., uncertainty analysis was employed. Numerous things might lead to uncertainties, such as shifting atmospheric conditions, deteriorating machine

Table 4 Proximate and ultimate analysis of SM and MI

Proximate and ultimate results of SM			
Proximate analysis	(wt. %)	Elemental analysis	(wt. %)
Volatile matter	76.98	Carbon (C)	55.3
Moisture content	7.01	Hydrogen (H)	4.56
Fixed carbon	14.72	Nitrogen (N)	0.34
Ash content	1.29	Sulfur (S)	0.60
-	-	Oxygen (O)	39.06
Total	100	Total	100
Proximate and ultimate results of MI			
Proximate analysis	(wt. %)	Elemental analysis	(wt. %)
Volatile matter	71.31	Carbon (C)	38.98
Moisture content	8.09	Hydrogen (H)	5.06
Fixed carbon	16.11	Nitrogen (N)	.08
Ash content	4.49	Sulfur (S)	-
-	-	Oxygen (O)	44.34
Total	100	Total	100

parts, the quality of the fuel being used, and more [52]. Moreover, varied mistakes from different calibration processes contributed to the uncertainty in the experiments [53]. Uncertainties primarily fall into two categories: random and fixed.

While random errors are caused by important amounts, fixed errors happen frequently. Using Eq. 17, the root mean square method was used in this experiment to carry out the combined uncertainty of the process [54]. The entire uncertainty is denoted by ΔU in this case, and the independent variables with independent errors are $y_1, y_2, y_3, \dots, y_n$. To determine the overall uncertainty of the proximate and ultimate analysis, feed materials samples were collected and carried out in the same process. It was discovered that there was roughly 2.43 total uncertainty in this trial approach.

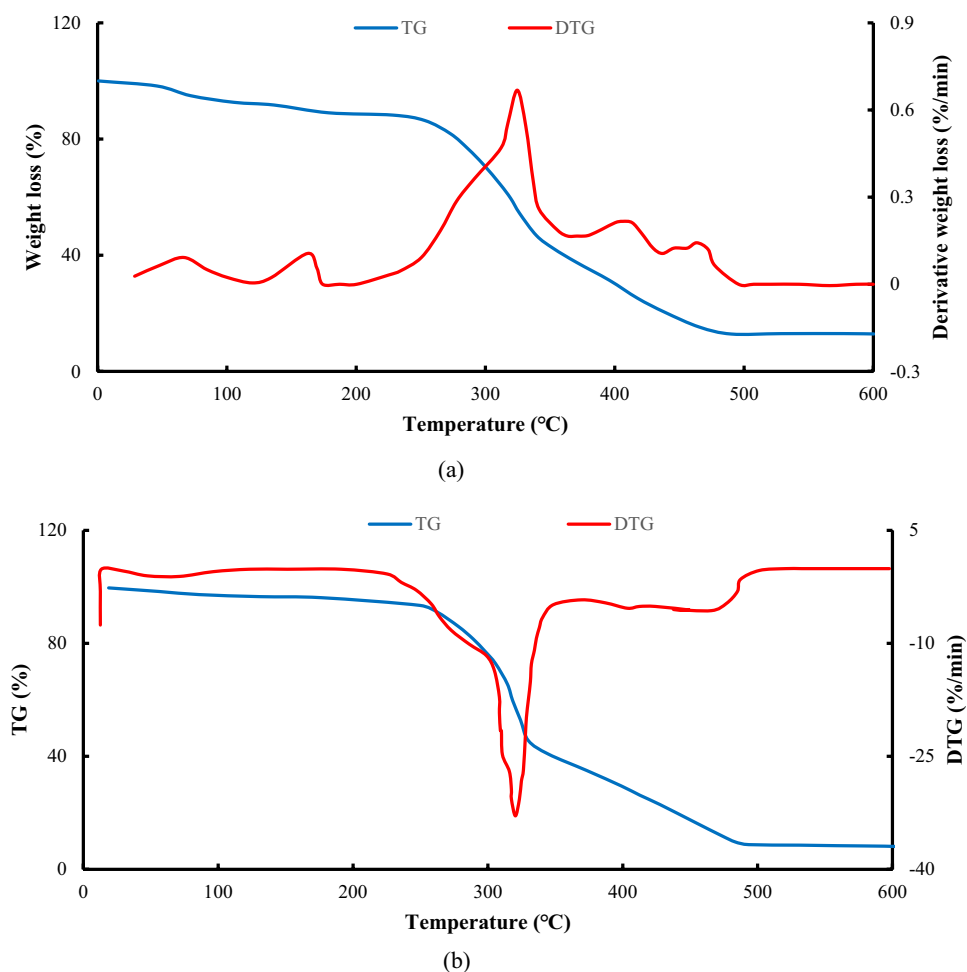
$$\Delta U = \sqrt{(y_1)^2 + (y_2)^2 + (y_3)^2 + \dots + (y_n)^2} \quad (17)$$

3 Results and discussion

3.1 Feed material characterization

The viability of feedstock for gasification depends upon the higher volatile matter. The proximate analysis of MI is shown in Table 4 which gives information about the volatile

Fig. 3 TG and DTG analysis of (a) MI wood and (b) SM wood



matter which is about 71.31%, 8.09% moisture, and 16.11% fixed carbon. For SM, the volatile matter is 76.98% and the moisture content is 7.01%. The performance of the gasifier is affected by the moisture content and fixed carbon percentages. The percentages of moisture should be as low as possible for better efficiency. The feedstock must be adequately dried to maintain the lowest possible moisture content.

The TG/DTG plot of MI and SM wood is shown in Fig. 3. It has been observed that the degradation of MI wood starts at 270 °C and ends at 490 °C. Between 200 °C and 350 °C, degradation occurs, with a maximum weight loss of about 70%. This process was hence referred to as the active pyrolysis stage and was considered to be an oil-producing stage. In addition, the largest loss of weight occurs between 255 °C and 490 °C for SM wood. As this is the range where maximum degradation occurs, this is the part where active pyrolysis of SM wood begins.

3.2 Effect of process parameters on cold gas efficiency and hydrogen yield

The particle size of feed samples has a great influence on cold gas efficiency and hydrogen yield. With increasing particle size, the hydrogen composition decreases significantly [55, 28].

The effect of particle size on cold gas efficiency (CGE) and hydrogen yield for SM and MI wood is presented in Fig. 4. As the particle size of SM wood increases from 22.5 mm to 55 mm, a discernible trend emerges. For the smallest particle size (22.5 mm), CGE stands at 79.21%, with hydrogen composition at 11.2%. However, as the particle size increases to the largest (55 mm), the CGE decreases to 71.43%, and the hydrogen composition diminishes to 8.6%. As the particle size of MI wood increases from 22.5 mm to 55 mm, a conspicuous trend emerges. For the smallest particle size (22.5 mm), CGE is measured at 75.66%, accompanied by a hydrogen composition of 12.1%. In contrast, for the largest particle size (55 mm), CGE decreases to 63.13%, while the hydrogen composition diminishes to 9%. These findings illustrate that larger SM and MI wood particle sizes are associated with reduced CGE and hydrogen yield during the gasification process. A similar trend is observed in the literature survey [27].

Equivalence ratio (ER) plays a vital role in cold gas efficiency and hydrogen yield in the gasification process. Equivalence ratios for successful gasification typically fall between 0.2 and 0.4 [38]. Pyrolysis predominates in gasification for equivalence ratios below 0.2 and combustion for equivalence ratios over 0.4 [33]. As illustrated in Fig. 5, for SM wood, as ER increases from 0.16 to 0.34, the data

Fig. 4 Hydrogen yield and cold gas efficiency of (a) SM wood and (b) MI wood gasification with variation of particle size

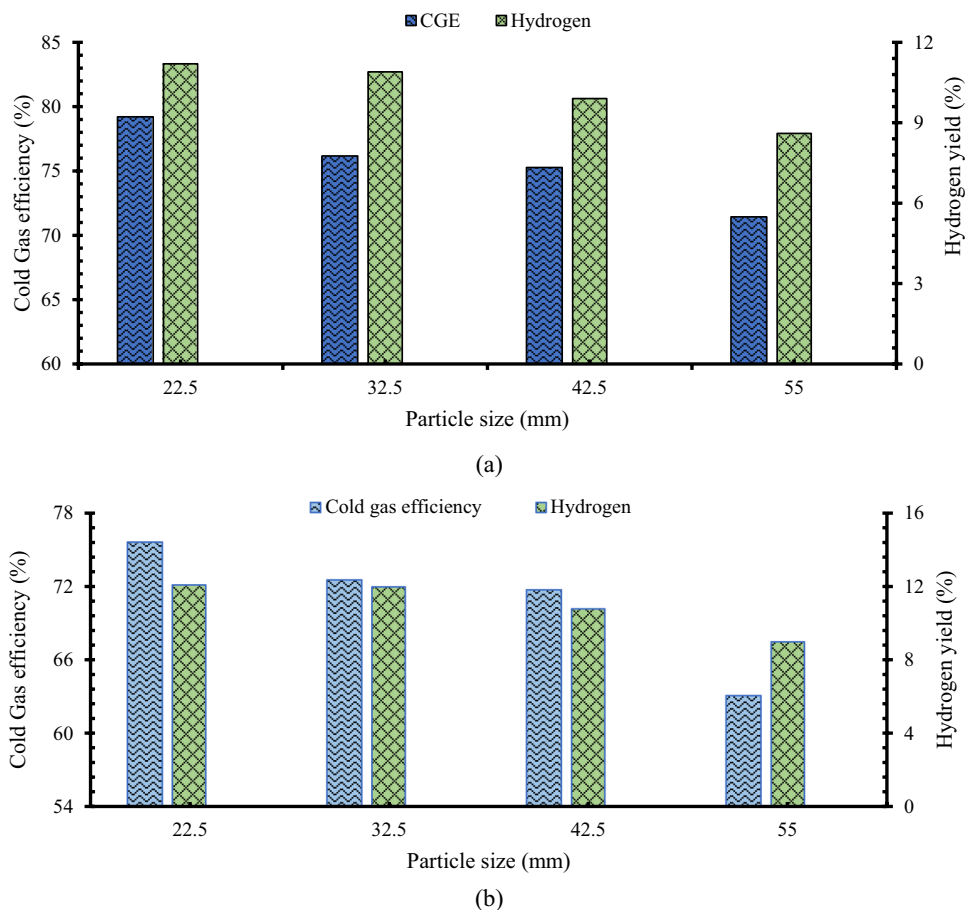
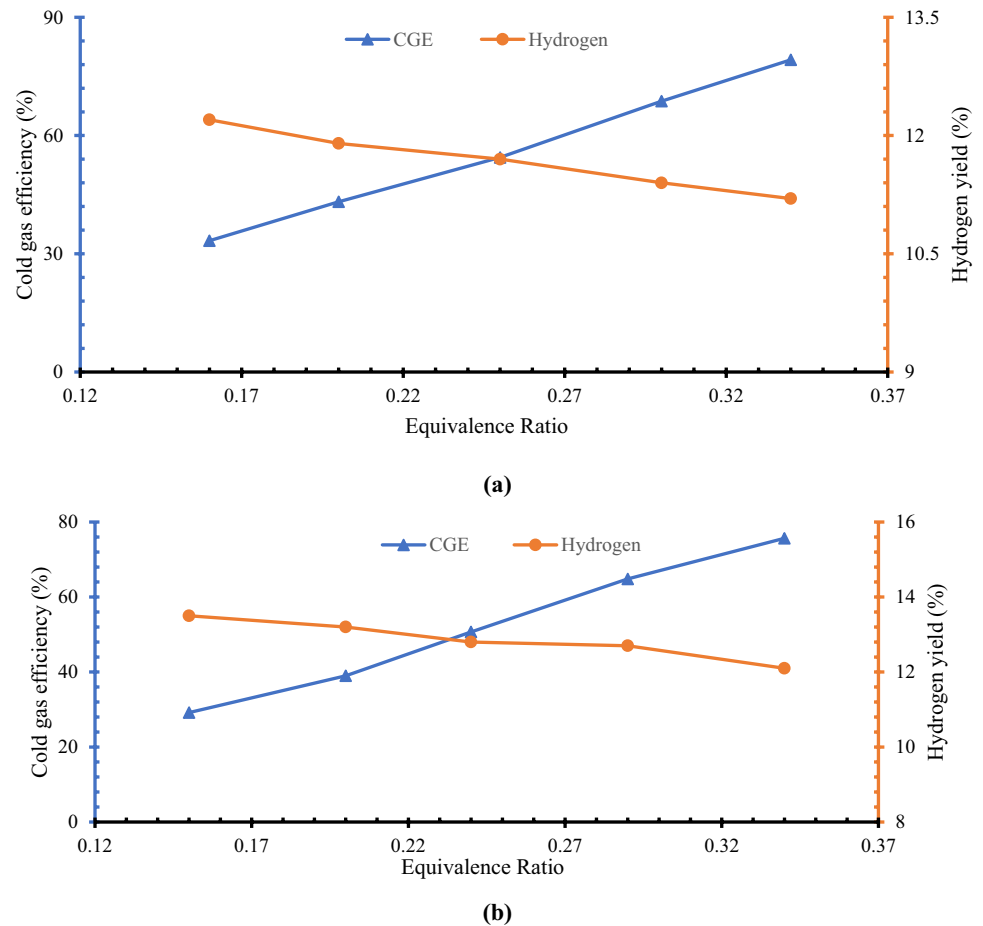


Fig. 5 Hydrogen yield and cold gas efficiency of (a) SM wood and (b) MI wood gasification with variation of equivalence ratio

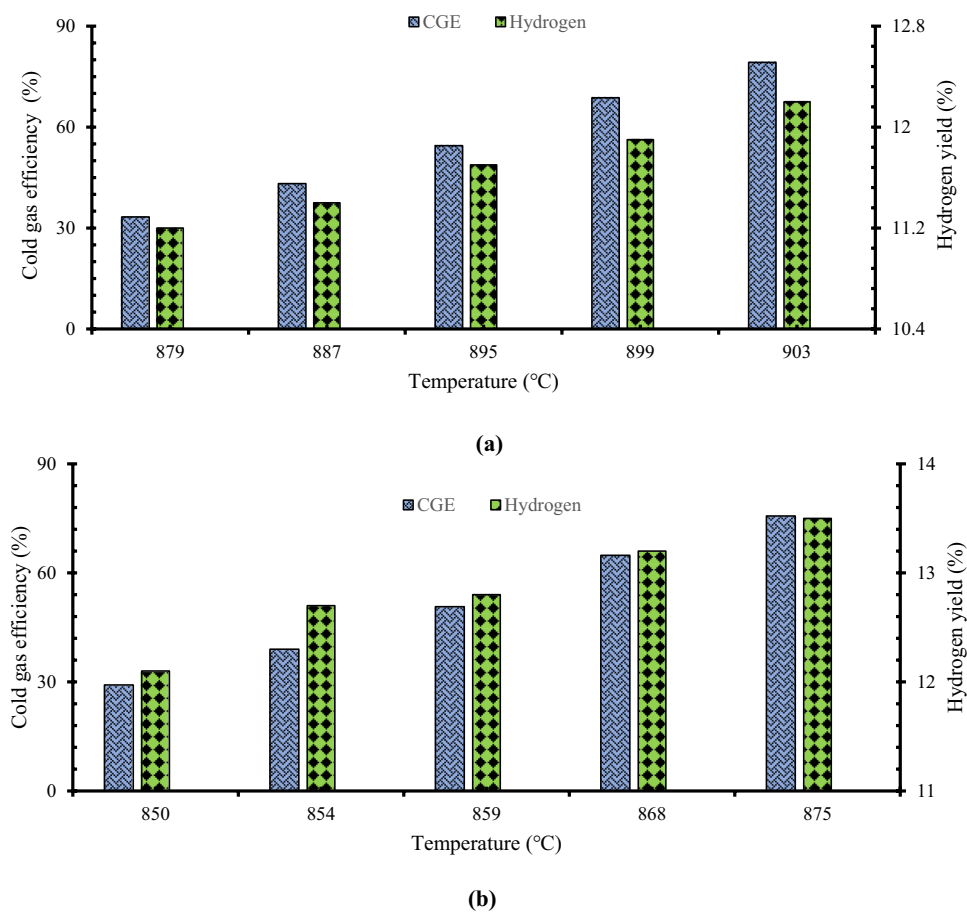


reveals substantial variations in both CGE and hydrogen yield. At the lowest ER value of 0.15, CGE is measured at 33.31%, with hydrogen yield at 12.2%. Conversely, at the highest ER value of 0.34, CGE experiences a significant increase to 79.21%, while hydrogen yield slightly decreases to 11.2%. As ER values increase from 0.15 to 0.34, notable trends emerge in both CGE and hydrogen yield. For MI wood, CGE is 29.18% with a hydrogen yield of 13.5% at the lower ER value of 0.15. At a higher ER value of 0.34, CGE improves significantly, reaching 75.66%, but hydrogen yield reduces somewhat to 12.1%. The findings highlight CGE's susceptibility to ER changes. A higher ER leads to a substantial increase in CGE, which aligns with the general understanding that increased oxygen supply can enhance combustion efficiency during gasification. Conversely, the hydrogen yield exhibits a slight decline with rising ER values. This phenomenon is attributed to the greater availability of oxygen in the gasification environment at higher ER, which promotes a reduction in hydrogen content in the resulting gas. Other studies also suggest more or less similar results [50].

The gasifier's high temperature accelerated endothermic char gasification and increased tar cracking, producing

syngas with greater calorific value [56]. The proportion of flammable gases like H_2 and CO rises as the gasification temperature rises [45, 56]. It is represented in Fig. 6 that, as the gasification temperature ranges from 879 to 899 °C for SM wood, significant changes in both CGE and hydrogen composition are evident. At the lower temperature of 879 °C, CGE registers at 33.31%, accompanied by a hydrogen yield of 12.2%. In contrast, at the higher temperature of 899 °C, CGE experiences a substantial improvement, reaching 79.21%, while hydrogen composition increases to 12.2%. As the gasification temperature varies from 850 to 875 °C for MI wood, significant changes in both CGE and hydrogen composition become evident. At a lower temperature of 850 °C, CGE is 29.18%, with a hydrogen yield of 12.1%. At a higher temperature of 875 °C, CGE improves significantly, reaching 75.66%, while hydrogen yield increases somewhat to 13.5%. The trends observed in this dataset underscore the pivotal role of temperature in the gasification of mango wood. Higher gasification temperatures result in a pronounced increase in CGE, aligning with the well-established principle that elevated temperatures enhance combustion efficiency, facilitating the release of more energy from the feedstock. Conversely, the hydrogen yield exhibits

Fig. 6 Hydrogen yield and cold gas efficiency of (a) SM wood and (b) MI wood gasification with variation of temperature



a slight decline with rising gasification temperature. This phenomenon is attributed to the higher temperatures promoting secondary reactions, which may favor the formation of other gaseous products at the expense of hydrogen yield. Similar results were found in the literature survey [57].

3.3 Effect of process parameters on syngas and methane yield

3.3.1 Effect of particle size on syngas composition for MI and SM wood

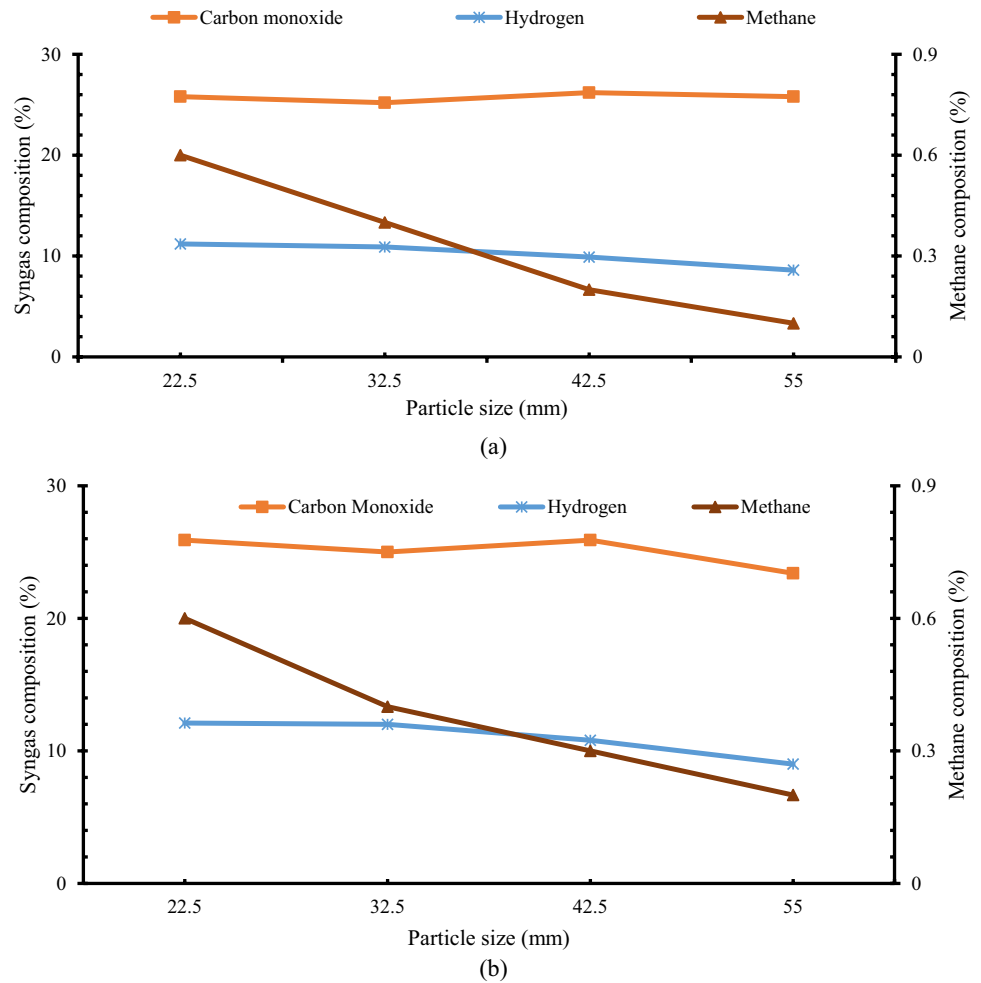
The particle size of feed samples has a significant impact on syngas composition. The hydrogen composition drops dramatically as particle size increases. In Fig. 7 it can be seen that as particle size increases from 22.5 mm to 55 mm, noteworthy trends in both syngas composition and methane composition are evident. At the smaller particle size of 22.5 mm, syngas composition is recorded at 37%, which consisted of 25.8% carbon monoxide and 11.2% Hydrogen with methane composition at 0.6%. In contrast, at the larger particle size of 55 mm, carbon monoxide composition reaches 25.8% with 8.6% of hydrogen, and methane composition declines further to 0.1%. For MI

wood, significant differences in syngas composition and methane composition become apparent when particle size increases from 22.5 mm to 55 mm. Carbon monoxide and hydrogen composition are measured at 25.9% and 12.1% respectively at the lower particle size of 22.5 mm, with methane composition at 0.6%. At a greater particle size of 55 mm, however, carbon monoxide and hydrogen composition are found to be 23.4% and 9% respectively, while methane composition drops to 0.2%. The literature survey also suggests more or less similar results [26].

3.3.2 Effect of equivalence ratio on syngas composition for MI and SM wood

With an increasing equivalence ratio, the tar component decreases and the syngas composition increases [58]. As ER values increase from 0.16 to 0.34, significant changes in both syngas composition and methane composition become evident as reported in Fig. 8. At the lower ER value of 0.16, carbon monoxide and hydrogen composition are recorded at 19.3% and 12.2%, with methane composition at 1.3%. Conversely, at the higher ER value of 0.34, carbon monoxide and hydrogen composition experience an increase, reaching 25.8% and 11.2%, while methane composition decreases to

Fig. 7 Effect of feedstock size on product yield for (a) SM and (b) MI wood



0.6% as shown in Fig. 8(a). For MI wood significant changes in carbon monoxide hydrogen composition and methane composition are observed as ER values grow from 0.15 to 0.34 as illustrated in Fig. 8(b). Carbon monoxide and hydrogen composition is 19.2% and 13.5% at the lower ER value of 0.15, with methane composition at 1.2%. In comparison, at a higher ER value of 0.34, syngas composition increases to 38% consisting of carbon monoxide and hydrogen at 25.9% and 12.1% respectively, while methane composition reduces to 0.6%. A literature survey provides a more or less similar result [50].

3.3.3 Effect of temperature on syngas composition for MI and SM wood

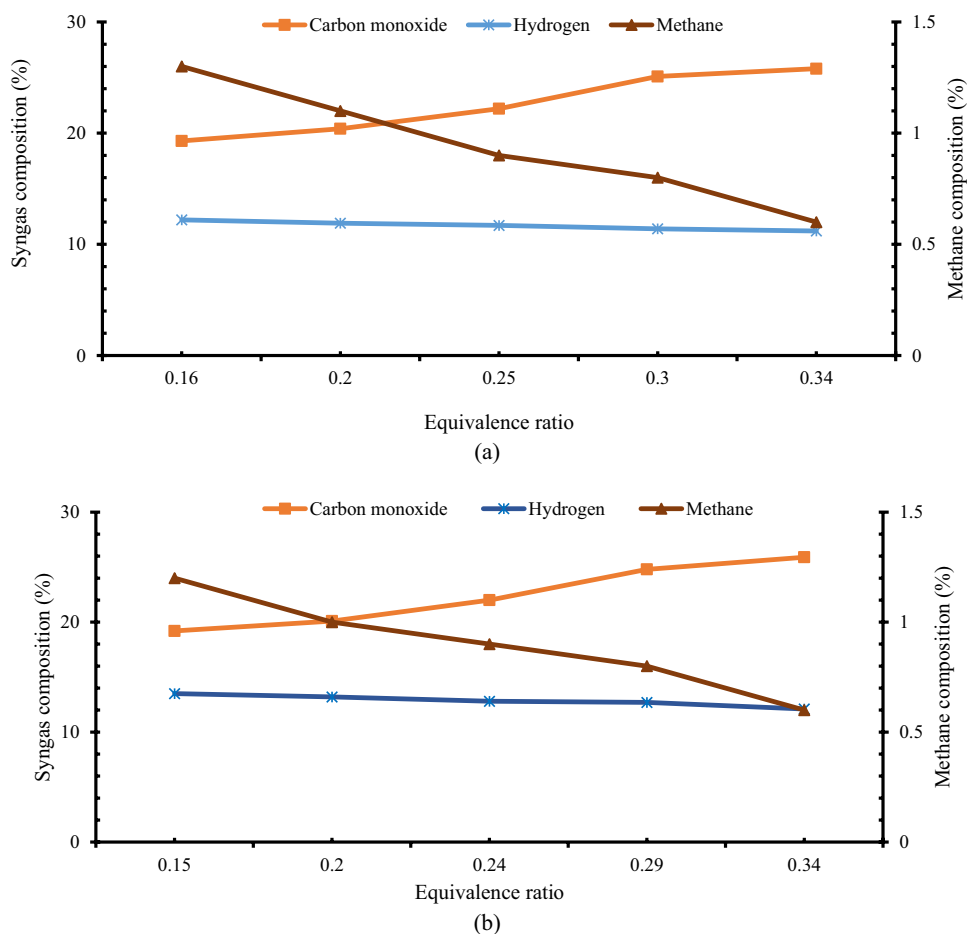
Typically, a temperature exceeding 800 °C is recommended in order to achieve optimal conversion rates and minimize the presence of tar within the resultant biogas. As presented in Fig. 9 the gasification temperature ranges from 879 °C to 903 °C, significant changes in both syngas composition and methane composition become apparent. At the lower temperature of 879 °C, syngas composition is recorded at 31.5%

(Carbon monoxide 19.3% and hydrogen 11.2%), with methane composition at 1.3%. In contrast, at the higher temperature of 903 °C, syngas composition experiences a notable improvement, reaching 37% (Carbon monoxide 25.8% and hydrogen 12.2%), while methane composition decreases to 0.6%. As seen for MI wood when the gasification temperature varies from 850 °C to 875 °C, substantial changes in both syngas composition and methane composition become apparent. At the lower temperature of 850 °C, Carbon Monoxide and Hydrogen composition is recorded at 19.2% and 12.1%, with methane composition at 1.2%. In contrast, at the higher temperature of 875 °C, carbon monoxide and hydrogen composition experience a notable change, reaching 25.9% and 13.5%, while methane composition decreases to 0.6%. Similar trend was found in other [57].

3.4 Optimization of the input parameters for obtaining efficiency and mathematical modeling

Using the Design Expert software-based Response Surface Methodology (RSM), the effects of various operating

Fig. 8 Effect of equivalence ratio on product yield for (a) SM and (b) MI wood



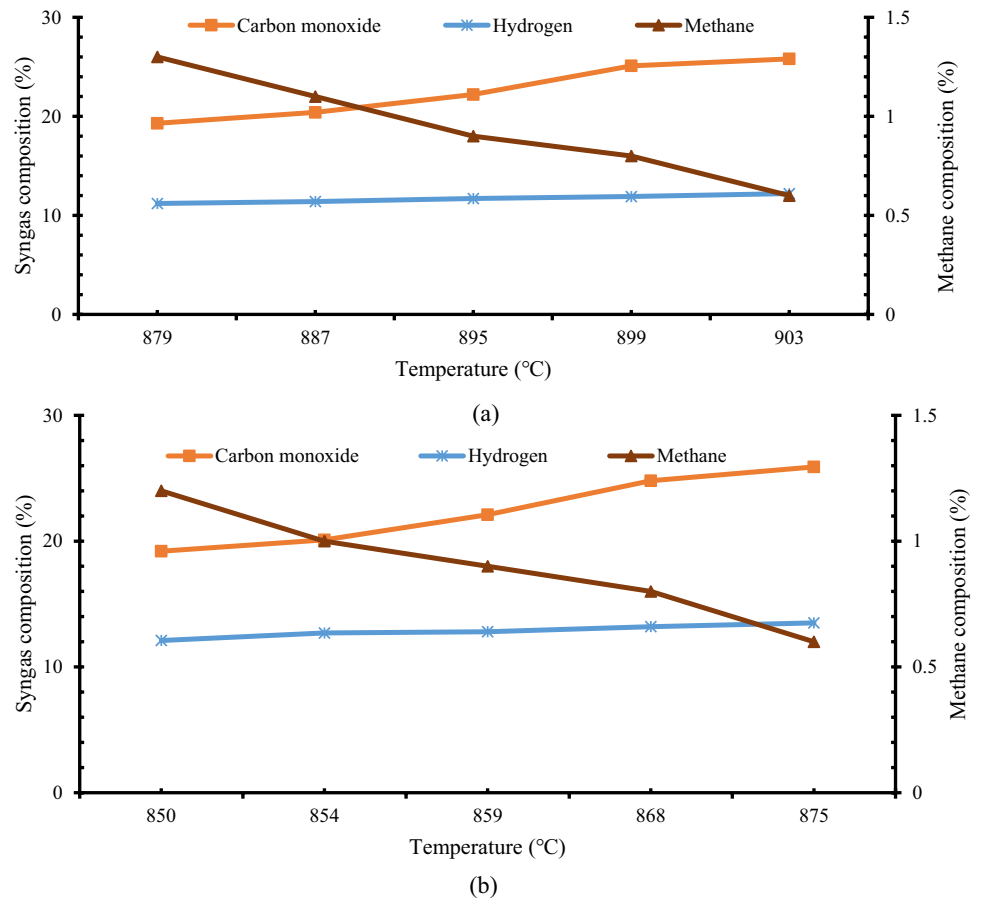
parameters were examined. The efficiency of the response was assessed, with consideration given to three major factors: particle size, equivalence ratio, and operating temperature. Optimization work was conducted through the utilization of the Design Expert software, specifically the Central Composite Design (CCD). The variables with the greatest impact on efficiency can be identified. An RSM model, guided by the trial run results (a total of 40–20 for each sample wood), was established with the support of the "Design Expert" software. The model fit-sequential for the assessment of cold gas efficiency is summarized in Tables 5, 6, 7, and 8. The Linear vs Mean and Quadratic versus Linear model, deemed acceptable starting point for modeling in the Analysis of Variance (ANOVA) model, was recommended. The examination of the influence of process parameters on pumping efficiency will play a vital role.

3.4.1 RSM modeling for determining response for hydrogen yield and cold gas efficiency for suggested model through ANOVA

Table 9 presents the results of the analysis of variance (ANOVA) for the proposed model of CGE. The model's

F-Value, determined to be 644.28, is deemed significant. This high "Model F-Value" result is attributed primarily to noise and has a probability of occurring at only 0.01%. The model's P-value of 0.0001 underscores its significance, as P-values exceeding 0.0010 are considered irrelevant [59]. The current ANOVA model includes essential model terms associated with the process variables, namely particle size (A), equivalence ratio (B), and operating temperature (C). ANOVA serves to highlight the main effects of these process factors, along with the model's error terms. The method for reacting effectively captures the potential process variables that could impact the CGE outcome.

Among the three process factors (A, B, and C), process factor B exhibits the highest F-Value (275.92), signifying that the equivalence ratio has the most pronounced influence on CGE. Conversely, temperature, represented by process factor A, demonstrates the least impact on CGE with the lowest F-Value (1.58). The relevant components are listed below in ascending order of importance: Operating temperature > Feed size > Equivalence ratio. This trend is also evident for MI wood and hydrogen composition, as shown in Tables 10, 11, and 12.

Fig. 9 Effect of temperature on product yield for (a) SM and (b) MI wood**Table 5** Summary of model fit-sequential for cold gas efficiency for gasification of SM wood

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Mean vs Total	54,092.48	1	54,092.48			
Linear vs Mean	5237.46	3	1745.82	644.28	< 0.0001	Suggested
2FI vs Linear	12.33	3	4.11	1.72	0.2114	
Quadratic vs 2FI	10.56	3	3.52	1.72	0.2255	
Cubic vs Quadratic	20.46	10	2.05			
Quartic vs Cubic	0.0000	0				Aliased
Residual	0.0000	0				
Total	59,373.29	20	2968.66			

Table 6 Summary of model fit-sequential for hydrogen composition for gasification of SM wood

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Mean vs Total	2283.38	1	2283.38			
Linear vs Mean	20.53	3	6.84	144.52	< 0.0001	
2FI vs Linear	0.5698	3	0.1899	13.15	0.0003	
Quadratic vs 2FI	0.1641	3	0.0547	23.14	< 0.0001	Suggested
Cubic vs Quadratic	0.0236	10	0.0024			
Quartic vs Cubic	0.0000	0				Aliased
Residual	0.0000	0				
Total	2304.67	20	115.23			

Table 7 Summary of model fit-sequential for cold gas efficiency for gasification of MI wood

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Mean vs Total	47,043.06	1	47,043.06			
Linear vs Mean	4429.37	3	1476.46	34.83	< 0.0001	
2FI vs Linear	421.47	3	140.49	7.12	0.0045	
Quadratic vs 2FI	232.40	3	77.47	31.92	< 0.0001	Suggested
Cubic vs Quadratic	24.27	10	2.43			
Quartic vs Cubic	0.0000	0				Aliased
Residual	0.0000	0				
Total	52,150.58	20	2607.53			

Table 8 Summary of model fit-sequential for hydrogen composition for gasification of MI wood

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Mean vs Total	2810.82	1	2810.82			
Linear vs Mean	23.39	3	7.80	34.65	< 0.0001	
2FI vs Linear	0.9099	3	0.3033	1.47	0.2697	
Quadratic vs 2FI	1.43	3	0.4773	3.79	0.0473	Suggested
Cubic vs Quadratic	1.26	10	0.1259			
Quartic vs Cubic	0.0000	0				Aliased
Residual	0.0000	0				
Total	2837.81	20	141.89			

3.4.2 Effect of process variables on product variables on hydrogen yield

With a very low *P*-value (*P* 0.0001), Fig. 10 demonstrates the 3D surface reactions of H₂ (vol%) generated by the integration effect of particle size and ER during SM and MI wood gasification. The tar cracking and reforming reactions (Eqs. 18–20), the water–gas reaction (Eq. 21), the Boudouard reaction (Eq. 22), and the exothermic water–gas shift reaction (Eq. 23), can all be linked to high H₂ concentrations in small particle size.

$$C_n H_m + n H_2 O = \left(n + \frac{m}{2} \right) H_2 + n CO \quad (18)$$

$$C_n H_m + n CO_2 = \left(\frac{m}{2} \right) H_2 + 2n CO \quad (19)$$

$$C_n H_m = \left(\frac{m}{2} \right) H_2 + n C \quad (20)$$



Figure 11 shows the 3D surface responses of H₂ (vol%) generated by the integration effect of temperature and ER during SM and MI wood gasification with a very low *P*-value (*P* 0.0001). Tar cracking and reforming processes, water–gas shift reactions, Boudouard reactions, and exothermic water–gas shift reactions have all been connected to high H₂ concentrations in small particle size.

As shown in Fig. 12, particle size has a bigger impact on the gasification performance of MI and SM wood than operating temperature. As previously stated, the H₂ percentage concentrations are mostly determined by the gasifier's operating temperature.

Table 9 The analysis of variance (ANOVA) of the suggested model for cold gas efficiency for gasification of SM wood

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	5237.46	3	1745.82	644.28	< 0.0001	significant
A-Feed Size	62.64	1	62.64	23.12	0.0002	
B-Equivalence Ratio	747.66	1	747.66	275.92	< 0.0001	
C-Temperature	4.29	1	4.29	1.58	0.2262	
Residual	43.36	16	2.71			
Cor Total	5280.81	19				

Table 10 The analysis of variance (ANOVA) of the suggested model for hydrogen composition for gasification of SM wood

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	21.26	9	2.36	999.05	< 0.0001	significant
A-Feed Size	0.7702	1	0.7702	325.69	< 0.0001	
B-Equivalence Ratio	0.2023	1	0.2023	85.55	< 0.0001	
C-Temperature	0.0354	1	0.0354	14.98	0.0031	
AB	0.0007	1	0.0007	0.3166	0.5860	
AC	0.0020	1	0.0020	0.8632	0.3747	
BC	0.0027	1	0.0027	1.16	0.3077	
A2	0.0955	1	0.0955	40.38	< 0.0001	
B2	0.0011	1	0.0011	0.4492	0.5179	
C2	0.0010	1	0.0010	0.4242	0.5295	
Residual	0.0236	10	0.0024			
Cor Total	21.29	19				

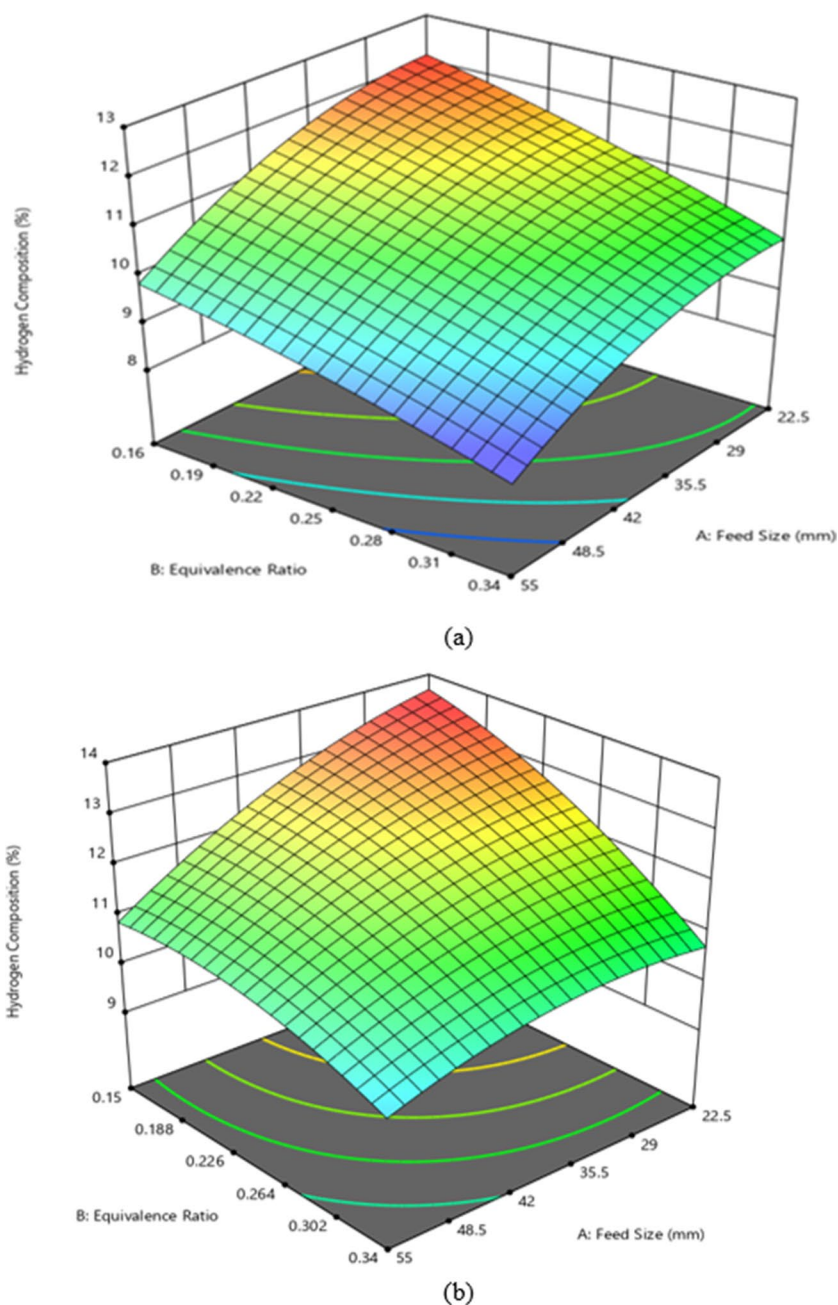
Table 11 The analysis of variance (ANOVA) of the suggested model for cold gas efficiency for gasification of MI wood

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	5083.25	9	564.81	232.69	< 0.0001	significant
A-Feed Size	11.20	1	11.20	4.61	0.0573	
B-Equivalence Ratio	427.91	1	427.91	176.29	< 0.0001	
C-Temperature	3.95	1	3.95	1.63	0.2307	
AB	74.51	1	74.51	30.70	0.0002	
AC	46.33	1	46.33	19.09	0.0014	
BC	156.92	1	156.92	64.65	< 0.0001	
A2	0.9207	1	0.9207	0.3793	0.5517	
B2	111.16	1	111.16	45.80	< 0.0001	
C2	39.58	1	39.58	16.30	0.0024	
Residual	24.27	10	2.43			
Cor Total	5107.52	19				

Table 12 The analysis of variance (ANOVA) of the suggested model for hydrogen composition for gasification of MI wood

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	25.73	9	2.86	22.71	< 0.0001	significant
A-Feed Size	0.2590	1	0.2590	2.06	0.1819	
B-Equivalence Ratio	0.7902	1	0.7902	6.28	0.0311	
C-Temperature	0.1508	1	0.1508	1.20	0.2993	
AB	0.1096	1	0.1096	0.8706	0.3728	
AC	0.4309	1	0.4309	3.42	0.0940	
BC	1.22	1	1.22	9.69	0.0110	
A2	0.0451	1	0.0451	0.3583	0.5627	
B2	0.3198	1	0.3198	2.54	0.1420	
C2	0.4981	1	0.4981	3.96	0.0747	
Residual	1.26	10	0.1259			
Cor Total	26.99	19				

Fig. 10 3D surface response of hydrogen composition for (a) SM wood and (b) MI wood in terms of ER and feed size



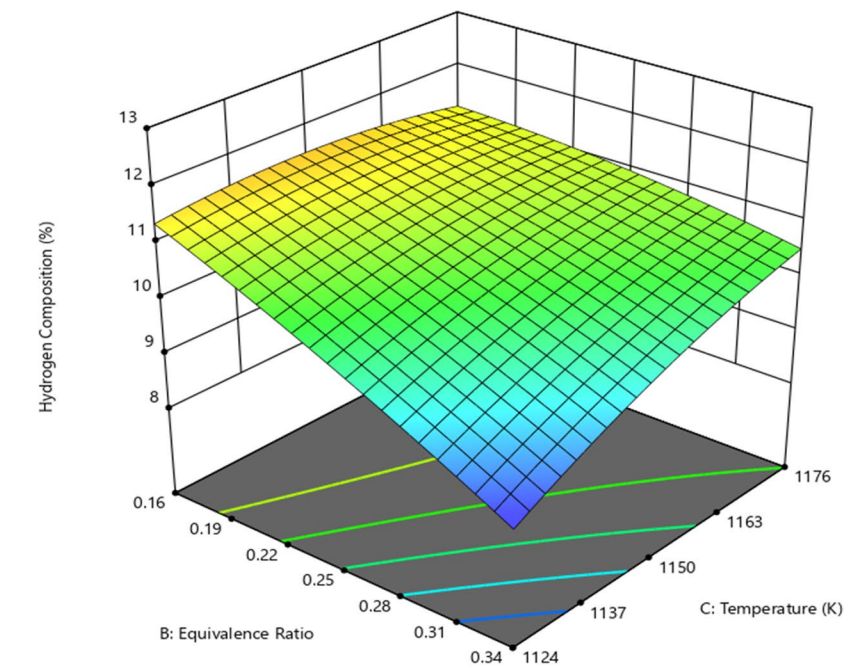
3.4.3 Effect of process variables on product variables on cold gas efficiency

Figures 13–15 illustrates the surface responses of cold gas efficiency for SM and MI wood as the particle size, temperature and ER changes. The CGE gradually increases as particle size decreases, temperature and ER increases. This difference results from the fact that smaller particles often undergo thermochemical reactions at a faster pace than larger ones, which raises the percentages of H_2 , CO, and

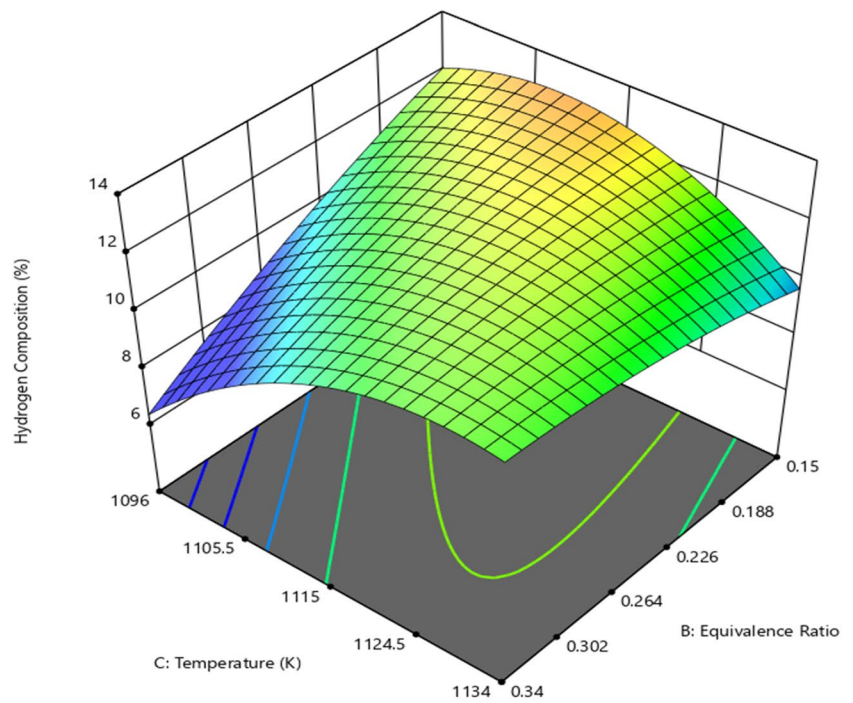
CH_4 , and improves HHV. There is a reduction of CGE as the particle size increase. This is because of the generation of low carbonaceous gas.

From Figs. 14 and 15 it is clear that the operating temperature shows a significant effect on the performance of the gasifier. As previously indicated, the gasifier's operating temperature, which significantly reflects the HHV value, determines the percentage concentrations of H_2 and CO. In every case the SM wood provides better performance. The same phenomena was observed by various other studies [60].

Fig. 11 3D surface response of hydrogen composition for (a) SM wood and (b) MI wood in terms of ER and temperature



(a)



(b)

Fig. 12 3D surface response of hydrogen composition for (a) SM wood and (b) MI wood in terms of temperature and feed size

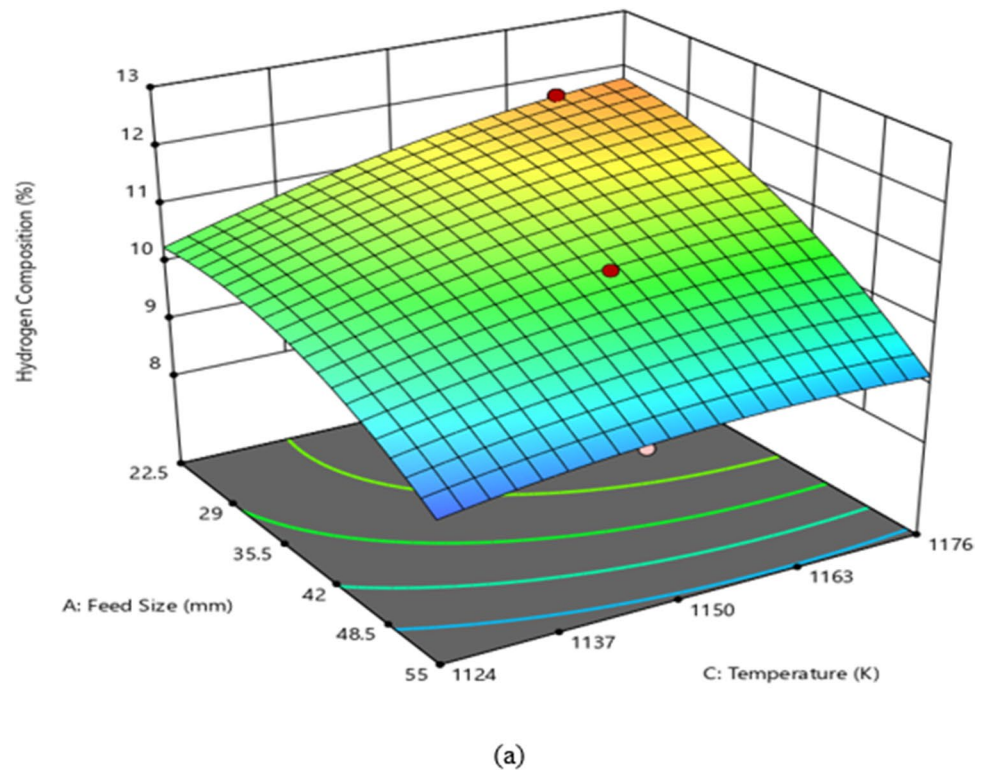
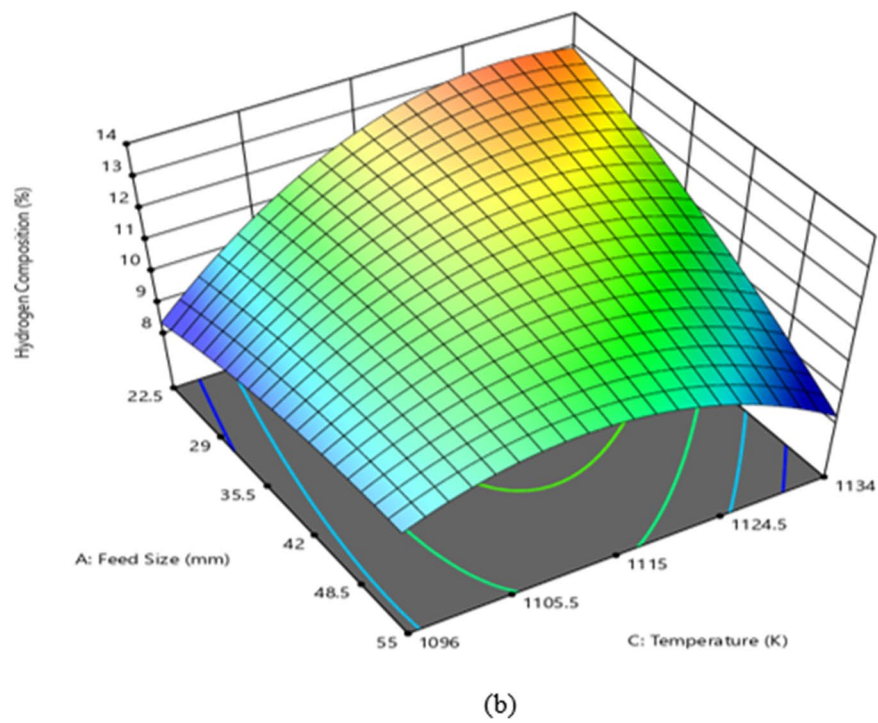


Fig. 13 3D surface response of CGE for (a) SM wood and (b) MI wood in terms of ER and feed size

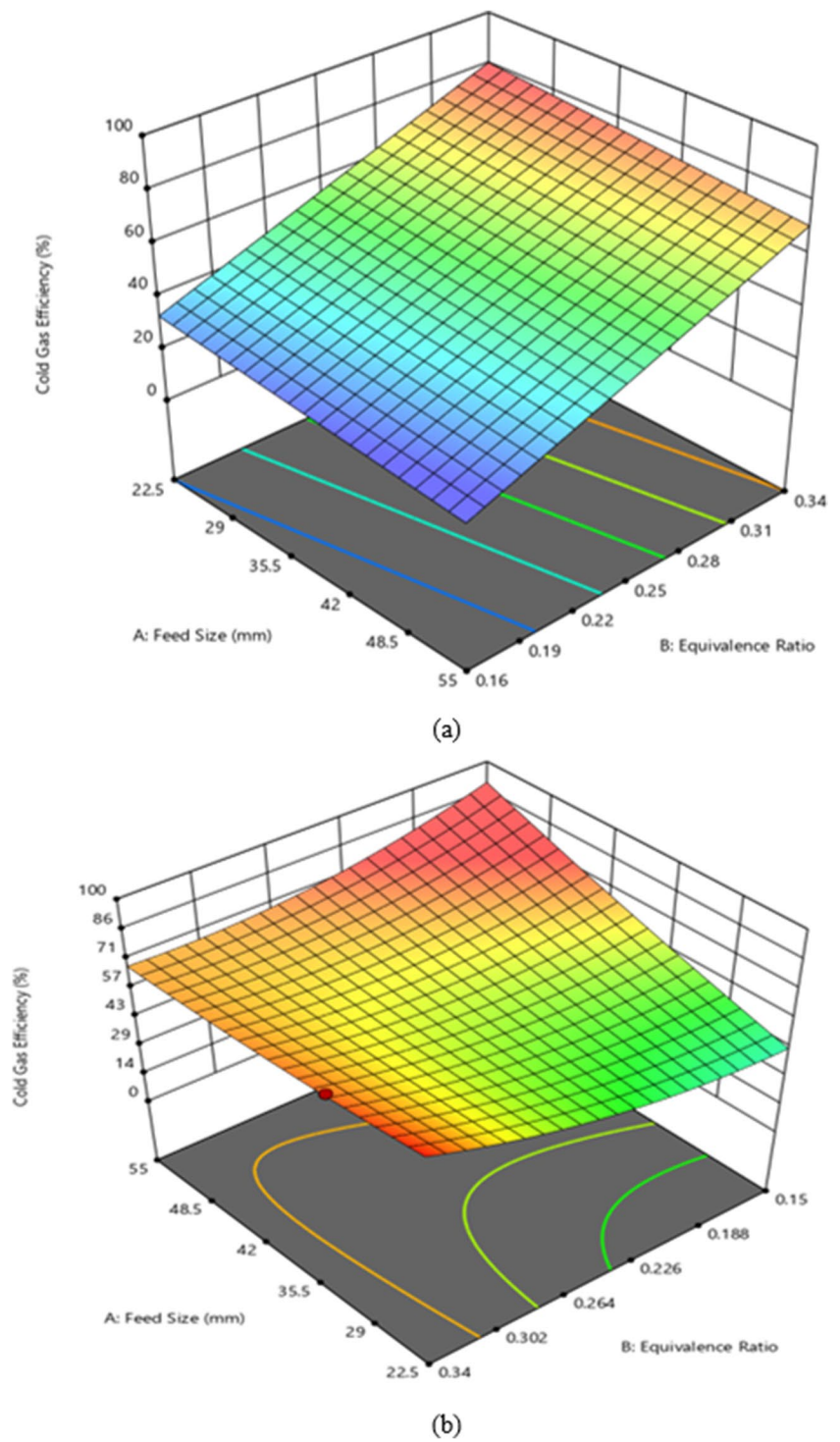
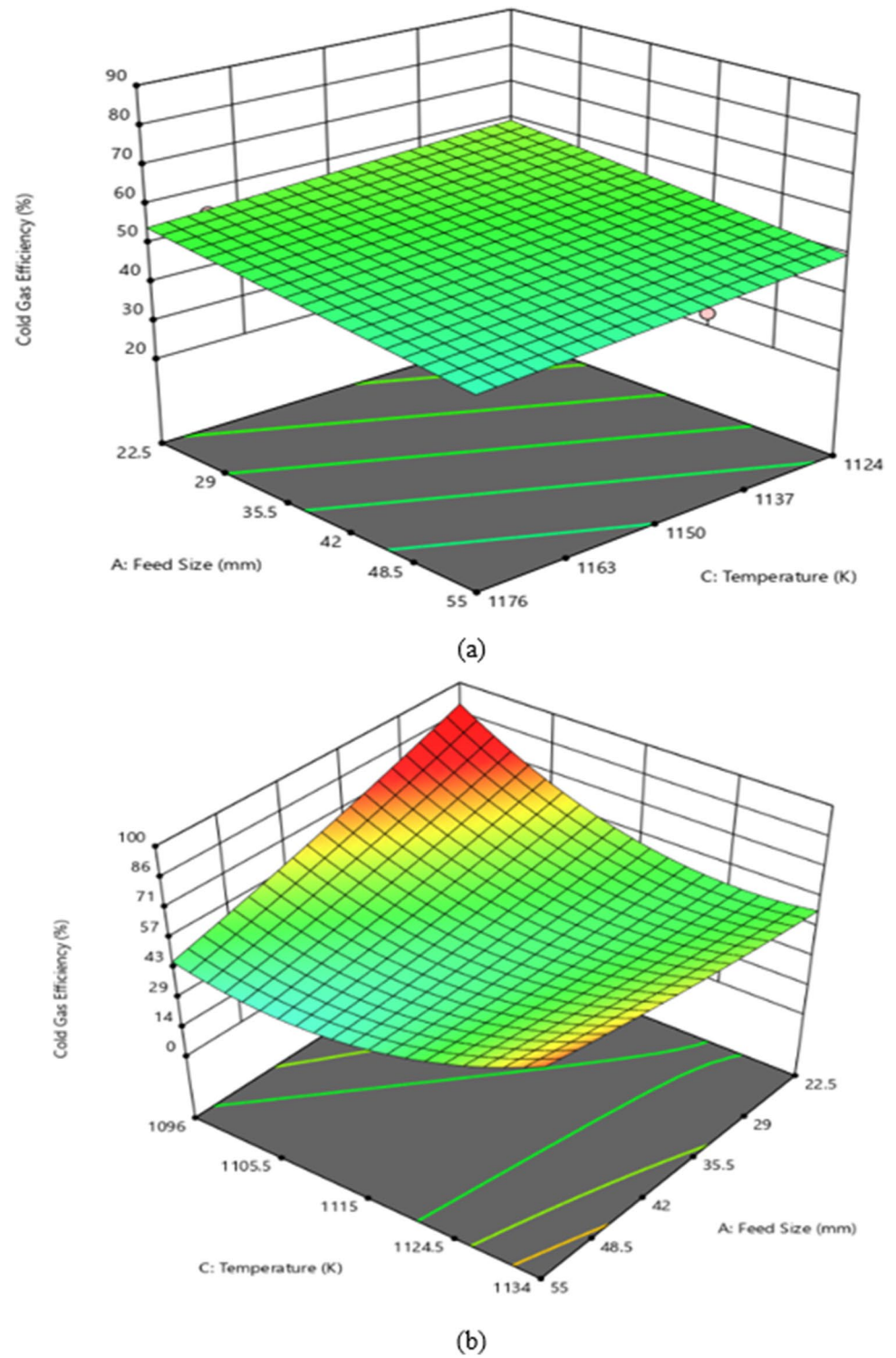


Fig. 14 3D surface response of CGE for (a) SM wood and (b) MI wood in terms of temperature and feed size



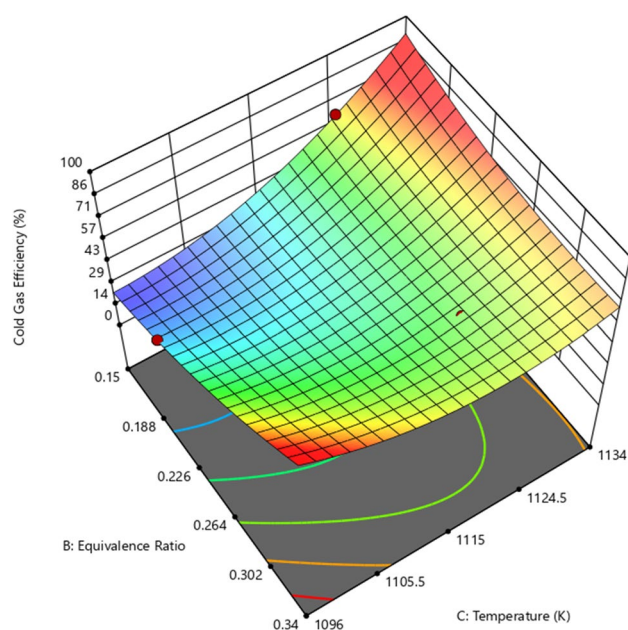


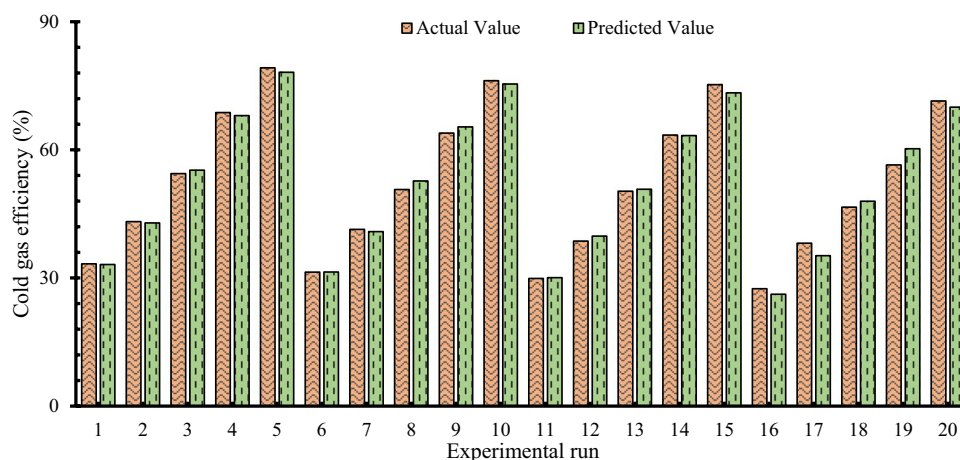
Fig. 15 3D surface response of CGE for MI wood in terms of ER and temperature

3.5 Mathematical modeling of optimize production yield

The input process parameters are optimized using design expert software to determine the maximum product yield. The calculated CGE is approximately 79.21% when the tests are conducted under the specified conditions, which is 1.21% lower than the expected value using RSM. A recent finding indicates that a low coefficient of variance, specifically $\leq 10\%$, is considered a dependable indicator of the expected model's ability to be replicated [61]. The model's

predictions for CGE and hydrogen composition are correct within the specified process parameters. The ultimate equation is presented concerning the tangible components. The equations that represent the real factors are given by Eq. 24, 25, 26, and 27. The equations (Eqs. 24–27) can be utilized to forecast the CGE (%) and hydrogen composition (wt.%) by inputting three process parameters: particle size (A), ER (B), and operating temperature (C). Furthermore, the existing data is partitioned into multiple subsets as a necessary step in training and validating the model. During each cycle, one subset is allocated for validation, while the remaining subsets are utilized for training the model. The three process parameters—particle size (A), equivalency ratio (B), and operating temperature (C)—can be entered as inputs into the final equations (Eq. 24–27) to anticipate the results of the cold gas efficiency and hydrogen composition. Separating the available data into several subsets is another step in the process of training and validating the model. Every iteration uses some selections for model training and validation, with the remaining subsets being used for training. Compared to hold-out validation, this method uses all available data for both training and validation, yielding a more reliable estimate of the model's performance. The experimental and expected reactions are visually depicted in Figs. 16, 17, 18 and 19. No unexpected changes have been observed in the model, indicating that the actual and predicted responses are satisfactory. Furthermore, the disparity between the actual (experimental) outcomes and the expected outcomes is insignificant. The observed values closely align with the projected values, suggesting that the model is a reliable tool for estimating the reaction. Consequently, it may be inferred that both CGE and hydrogen composition mathematical modeling are reliable.

Fig. 16 Difference between predicted and actual cold gas efficiency for SM wood gasification



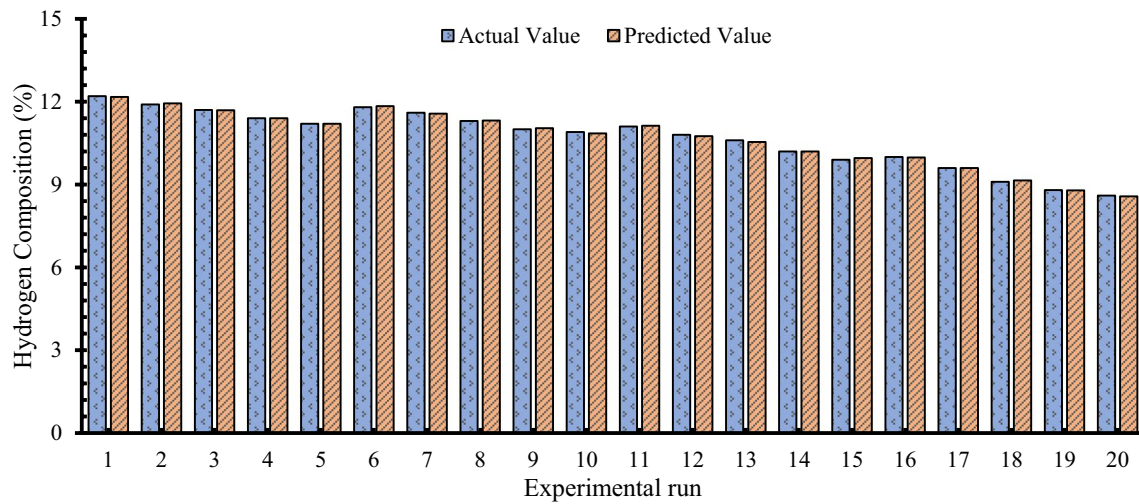


Fig. 17 Difference between predicted and actual hydrogen composition for SM wood gasification

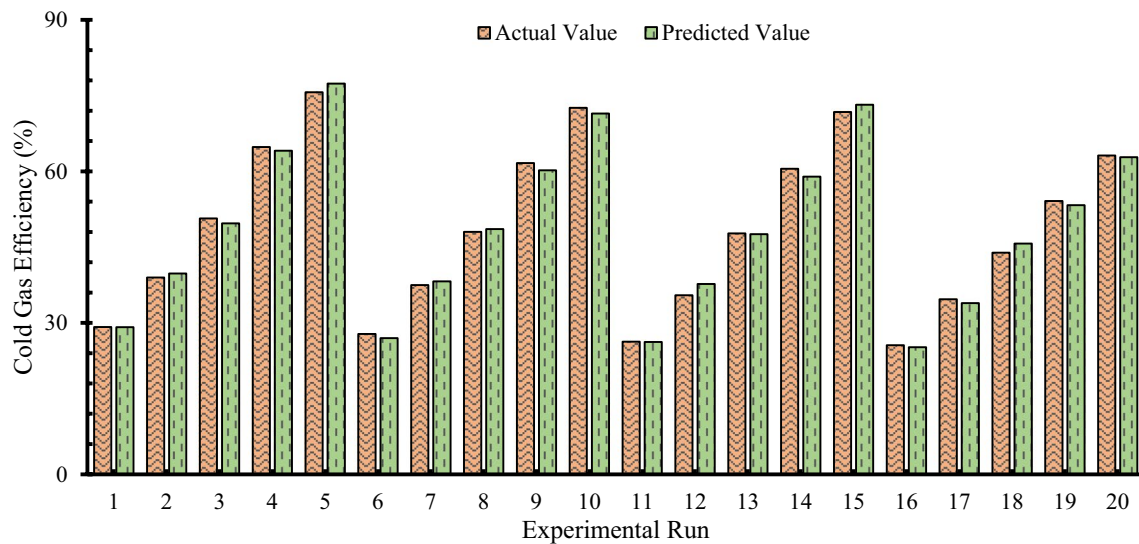


Fig. 18 Difference between predicted and actual cold gas efficiency for MI wood gasification

For SM wood,

$$\begin{aligned} \text{Predicted } \eta_{CG} = & 113.69742 - 0.294947A \\ & + 263.46954B - 0.100753C \end{aligned} \quad (24)$$

$$\begin{aligned} \text{Predicted } x_{H_2} = & -416.54413 + 0.841641A - 272.54176B + 0.760061C \\ & + 0.078441AB - 0.000672AC + 0.0232732BC \\ & - 0.001966A^2 - 16.25578B^2 - 0.000336C^2 \end{aligned} \quad (25)$$

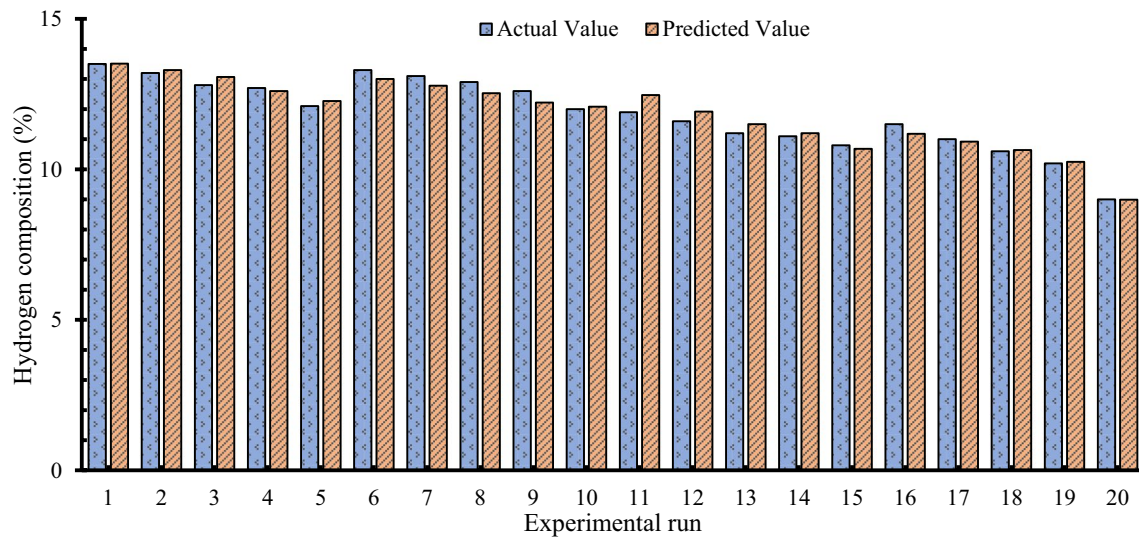


Fig. 19 Difference between predicted and actual hydrogen composition for SM wood gasification

For MI wood,

$$\begin{aligned} \text{Predicted } \eta_{CG} = & 54337.15559 - 56.18916A + 13241.59253B \\ & - 98.20019C - 8.598AB + 0.051495AC - 11.71079BC \\ & + 0.006804A^2 + 811.64772B^2 + 0.044347C^2 \end{aligned} \quad (26)$$

$$\begin{aligned} \text{Predicted } x_{H_2} = & -6141.72907 + 5.52006A - 1153.23589B + 11.06895C \\ & + 0.329718AB - 0.004966AC + 1.03238BC \\ & - 0.001506A^2 - 43.53186B^2 - 0.004975C^2 \end{aligned} \quad (27)$$

where, η_{CG} = Cold gas efficiency, x_{H_2} = In hydrogen composition, A is particle size, B is ER, and C is operating temperature.

3.6 Economic indicators

Various economic indicators of the project are presented in Table 13. It has been found that the estimated hydrogen production from the 178 gasification plants having 10 tons/day capacity was 60.83 k tons annually. The gasification unit had an annual energy yield of 535.96 GWh, but over the course of its useful life, it produced over 10,719.2 GWh overall. The calculated levelized cost of energy was found 0.1116 \$/kWh. The estimated payback period and internal rate of return of the proposed gasification plants were found to be 10.7 years and 4% respectively. In addition, the annual CO₂ emission reduction from the proposed plants was 443.78 k tons.

From the economic analysis of the gasification plants, it is clear that a significant amount of CO₂ emission can be eliminated if the project can be implemented. The low cost of energy

and payback period makes the project very attractive. This technology could therefore be a viable and alluring answer at this critical juncture in the nation's energy need. This technology can manage a significant volume of hazardous solid waste and

Table 13 Summary of various economic indicators

Components	Unit	Value
Initial investment cost	M\$	534
Operation & maintenance cost	M\$	69.62
Total Life Cycle Cost	M\$	570.55
Tax paid on profit	M\$	266.65
Net present value	M\$	211.98
Investment Payback Period	Y	10.7
Levelized Cost of Energy	\$/kWh	0.1116
Revenue	M\$	1136.24
Profit	M\$	1066.62
Net Cash Flow	M\$	799.96
Internal Rate of Return	%	4
CO ₂ emission reduction per year	K ton	443.78

wood waste and mitigate Bangladesh's unemployment problem and dependence on imported petroleum crude oil. The produced Hydrogen can provide an alternative source of energy leading to a cleaner and better future.

4 Conclusions

The purpose of this study was to examine the possibility of using gasification of SM and MI wood as an alternative fuel to mitigate environmental pollution and energy scarcity. Through the use of RSM's CCD and proximate, ultimate, and TG-DTG analyses, the study improved product production by optimizing the operational parameters. Under ideal circumstances, the gasification process produced notable CO, H₂, and CH₄ yields, with cold gas efficiencies for SM and MI wood of 79.2% and 75.7%, respectively. The best parameters for optimizing product yield, according to the study, are an equivalency ratio (ER) of 0.34, a lower feedstock size of 22.5 mm, and an operating temperature of 903 °C. With SM wood yielding 11.2% hydrogen and 78.16% efficiency and MI wood yielding 12.85% hydrogen and 76% efficiency, RSM analysis verified these parameters for attaining the maximum hydrogen yield and cold gas efficiency. ANOVA modeling demonstrated a strong correlation between experimental and projected values, highlighting the model's dependability. A 20-year gasification project with a payback period of 10.7 years and a levelized cost of energy (LCOE) of \$0.1116/kWh could be feasible, according to an economic feasibility analysis. These results show that wood waste can be repurposed, and sustainable hydrogen can be produced using SM and MI wood gasification, which might greatly benefit Bangladesh by lowering energy scarcity. To further improve the efficiency and viability of gasification plants, future studies should examine energy and exergy analysis during syngas generation. Further research may be conducted to determine the energy, and exergy analysis of the gasifier plant in the syngas production stage.

Nomenclature SM: *Swietenia macrophylla* (Mahogany); MI: *Mangifera indica* (Mango); CO: Carbon monoxide; H₂: Hydrogen; CH₄: Methane; GHG: Greenhouse Gas; RSM: Response surface methodology; ANOVA: Analysis of variance; IRR: Internal rate of return; SO_x: Sulfur Oxide; NO_x: Nitrogen oxide; IPBP: Investment payback period; TLCC: Total life cycle cost; LCOE: Levelized cost of energy; NPV: Net present value; TG: Thermogravimetric; DTG: Derivative thermogravimetric; HHV: Higher heating value; LHV: Lower heating value; ER: Equivalence ratio; CGE: Cold gas efficiency; η_{CG} : Cold gas efficiency; x_{H_2} : Hydrogen composition

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Declarations

Statements and Declarations The authors affirm that this manuscript is original, has not been published before, and is not currently being considered for publication elsewhere.

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