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Energy and exergy analysis of syngas production from different biomasses through air-steam gasification

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Abstract Gasification is a thermo-chemical reaction which converts biomass into fuel gases in a reactor. The efficiency of conversion depends on the effective working of the gasifier. The first step in the conversion process is the selection of a suitable feedstock capable of generating more gaseous fuels. This paper analyses the performance of different biomasses during gasification through energy and exergy analysis. A quasi-equilibrium model is developed to simulate and compare the feasibility of different biomass materials as gasifier feedstock. Parametric studies are conducted to analyze the effect of temperature, steam to biomass ratio and equivalence ratio on energy and exergy efficiencies. Of the biomasses considered, sawdust has the highest energy and exergy efficiencies and lowest irreversibility. At a gasification temperature of 1000 K, the steam to biomass ratio of unity and the equivalence ratio of 0.25, the energy efficiency, exergy efficiency and irreversibility of sawdust are 35.62%, 36.98% and 10.62 MJ/kg, respectively. It is also inferred that the biomass with lower ash content and higher carbon content contributes to maximum energy and exergy efficiencies.

Keywords gasification, modeling, energy, exergy, syngas

1 Introduction

Biomass is the largest renewable energy source that contributes to 15% of the world's primary energy consumption [1]. Apart from its low energy density compared to conventional fuels, its renewability, ample availability and carbon neutrality make it a potential replacement option for fossil fuels. However, direct use of

biomass is not economical. Therefore, suitable energy efficient conversion techniques are required to enhance its quality. Biochemical and thermo-chemical conversion routes are the widely used methods to extract energy from biomass.

Combustion, pyrolysis and gasification are the major thermo-chemical methods suitable for cellulosic materials like biomass [2]. Direct combustion is the conventional method, even though it is the least efficient one and is characterized by large CO₂ emission [3]. Of the three methods, gasification is the most effective conversion one because of its higher conversion rate in comparison with combustion and pyrolysis [4]. Biomass gasification is a complicated process influenced by several parameters like the type of the reactor, the reactor temperature and pressure, the type of gasifying agent, the biomass composition and moisture content, etc. [5]. So a thorough knowledge of the effect of these parameters on gasification process is essential for the successful design of a gasification system. This can be achieved by energy and exergy analyses which can assist in the design, performance prediction and optimization of such systems. Even though first law analysis is widely used for the performance assessment of a system, the evaluation of the quality of energy, which gets depleted due to the associated irreversibilities, is not accounted. Thus it is advisable to perform exergy analysis to identify the potential locations where there is scope for further improvement. Saidur et al. [6] presented a comprehensive review on the exergy analysis of different kinds of feedstocks like woody, agricultural, herbaceous, aquatic, contaminated and industrial biomasses. Hydrogen, a clean fuel with highest energy content on mass basis, is one of the major constituents of syngas generated from biomass gasification. It can be considered as a future fuel if its availability is ensured from a renewable energy source like biomass. Many researchers analyzed the effect of operating parameters on energy and exergy efficiencies of hydrogen generation via biomass gasification [7–11]. The effect of biomass moisture content and gasifying medium on gasification efficiency in air and

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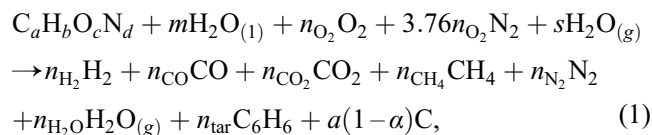
steam gasification of sawdust was analyzed by Hosseini et al. [12]. They found that exergy efficiency is higher when air was used as the gasifying agent and biomass moisture content had an adverse effect on exergy efficiency irrespective of the gasifying agent. Adverse effect of biomass moisture content on second law efficiency was also reported by Jarunthammachote and Dutta [13] and Karamarkovic and Karamarkovic [14] for air gasification of municipal solid waste, and by Pellegrini and de Oliveira [15] for air-steam gasification of sugarcane bagasse. Srinivas et al. [16] reported the adverse effect of relative air-fuel ratio and steam-fuel ratio on the lower heating value of syngas and exergy efficiency. Parametric study to compare the potential of different biomasses in air gasification was performed by Zhang et al. [17]. They found that the biomass with a lower ash content contributes to higher exergy values. Thus previous studies suggest exergy analysis as an alternative method to select the most efficient and convenient biomass, with suitable operating conditions, by accounting the irreversibilities associated with it in gasification process.

No work so far has reported the comparative evaluation of air-steam gasification performance of different feedstocks through exergy analysis. Equilibrium models, kinetic models and computational fluid dynamic models are widely used to simulate the gasification process. Even though kinetic and computational fluid dynamic models can provide more details like spatial and temporal variation of parameters, they are comparatively complex. On the other hand, sufficient data required for energy and exergy analysis of biomass gasification process can be obtained from relatively simpler quasi-equilibrium models [13,14]. This paper envisages the investigation on the performance of gaseous fuel generation from five different locally available biomasses, namely coconut shell, rice husk, sawdust, coir pith and rubber seed shell through not only energy and but also exergy analysis using the output of a quasi-equilibrium model incorporating the effect of char and tar formed during gasification.

2 Stoichiometric equilibrium model

Assumptions used for developing the steady-state model for air-steam biomass gasification are that gasifier is a steady-state system with uniform temperature and pressure throughout; the residence time of the gases in the gasifier is high enough to establish thermodynamic equilibrium; all the gases exhibit ideal behavior; gases, except H_2 , CO , CO_2 , CH_4 and N_2 , are negligible in composition; N_2 is treated as inert in the entire process; steam is supplied at 300°C and 1 bar; and char and tar are assumed as carbon and benzene, respectively.

Considering biomass as $C_aH_bO_cN_d$, the overall gasification process can be represented as



where a , b , c and d are respectively the number of the atoms of carbon, hydrogen, oxygen, and nitrogen per mole of dry and ash free biomass, n is the number of moles of respective components, s , m and n_{tar} are the number of moles of steam, moisture and tar, respectively.

The char conversion factor is given by [18]

$$\alpha = 0.901 + 0.439(1 - e^{(-ER + 0.0003T)}). \quad (2)$$

Tar yield is estimated as a weight percentage of the total gasification product as [7]

$$Tar_{wt\%} = 35.98e^{(-0.00298T)}. \quad (3)$$

Considering elemental balance,
Carbon

$$n_{CO} + n_{CO_2} + n_{CH_4} + 6n_{tar} + a(1-\alpha) - a = 0, \quad (4)$$

Hydrogen

$$2n_{H_2} + 4n_{CH_4} + 2n_{H_2O} + 6n_{tar} - b - 2m - 2s = 0, \quad (5)$$

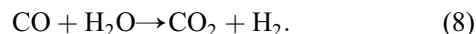
Oxygen

$$n_{CO} + 2n_{CO_2} + n_{H_2O} - c - 2n_{O_2} - m - s = 0, \quad (6)$$

Nitrogen

$$2n_{N_2} - d - 7.52n_{O_2} = 0, \quad (7)$$

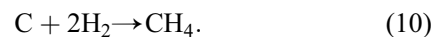
Water gas shift reaction



Equilibrium constant for water gas shift reaction is

$$K_1 = \frac{n_{CO_2}n_{H_2}}{n_{CO}n_{H_2O}}. \quad (9)$$

Methanation reaction is



Equilibrium constant for methanation reaction is

$$K_2 = \frac{n_{total}n_{CH_4}}{(n_{H_2})^2}. \quad (11)$$

The equilibrium constants of methanation and water gas shift reactions can be represented in terms of temperature [19]. The final product gas composition is obtained by solving Eqs. (4)–(7), (9) and (11) using the Newton-Rapson method in Matlab. The lower heating value of the product gas is shown as [20]

$$LHV = 10.79X_{H_2} + 12.26X_{CO} + 35.81Y_{CH_4}. \quad (12)$$

3 Model validation and non-equilibrium factors

The accuracy of the model is checked by comparing the model-predicted gas composition with that of the experimental one [21] and the deviation is quantified as 4.72 using root mean square (RMS) error

$$\text{RMS} = \sqrt{\frac{(X_e - X_p)^2}{N}}, \quad (13)$$

where X_p , X_e , and N are the model value, the experimental value, and the number of observations, respectively. It is found that the model over predicted H_2 and CO concentrations but under predicted CO_2 and CH_4 concentrations. Similar predictions were noticed by Melgar et al. [22] when they compared the model-predicted results with the experimental work of Jayah et al. [23]. The model is modified for better prediction by multiplying equilibrium constants K_1 and K_2 with suitable coefficients ($C_1 = 0.12e^{3.2\text{ER}}$ and $C_2 = 41-50\text{ER}$) to reduce the RMS error from 4.72 to a minimum of 1.37 [18]. The detailed model development, modification and preliminary analysis for biomass comparison using gas composition were done [24]. This part of the work deals with the comparison of exergy and energy efficiencies of syngas production from rice husk, coconut shell, sawdust, coir pith and rubber seed shell through air-steam gasification.

4 Energy and exergy analysis

4.1 Energy balance

Applying the energy balance to the system by considering negligible heat loss gives

$$\sum H_{\text{in}} = \sum H_{\text{out}}, \quad (14)$$

where $\sum H_{\text{in}}$ and $\sum H_{\text{out}}$ are the sums of the enthalpies of all the streams entering and leaving, respectively.

The energy efficiency of the gasification process is [24]

$$\eta_{\text{En}} = \frac{\text{Energy content in the product gas}}{\text{Energy content in biomass} + \text{Energy content in steam}}. \quad (15)$$

4.2 Exergy balance

The energy balance for a process can easily be made as the exergy received by a process is the sum of the exergy delivered and the exergy destructed (irreversibility) during the process. The irreversibility (I) associated with the process is obtained by applying the second law of thermodynamics [8]

$$I = \dot{E}x_{\text{reactants}} - \dot{E}x_{\text{products}}, \quad (16)$$

where $\dot{E}x_{\text{reactants}}$ and $\dot{E}x_{\text{products}}$ are the exergy rate associated with the reactants and the products, respectively.

The specific flow exergy associated with a particular state is expressed as the sum of chemical and physical exergies [8]

$$Ex_{\text{total}} = Ex_{\text{physical}} + Ex_{\text{chemical}}. \quad (17)$$

The physical exergy is caused by the difference in the pressure and temperature of the stream with respect to standard conditions of pressure ($P_0 = 1 \text{ atm}$) and temperature ($T_0 = 298 \text{ K}$). The physical exergy of each component is defined as

$$Ex_{\text{physical}} = h - h_0 - T_0(s - s_0), \quad (18)$$

$$h - h_0 = \int_{T_0}^T c_p dT, \quad (19)$$

$$s - s_0 = \int_{T_0}^T \frac{c_p}{T} dT, \quad (20)$$

where h , h_0 , s and s_0 are the specific enthalpy and specific entropy in the specified state and standard state, respectively. The constant specific heat (c_p) for each constituent is given in Table 1 as a function of temperature.

The physical exergy of the biomass is neglected as it is fed at ambient condition whereas the chemical exergy depends on the chemical composition of the biomass [28]

$$Ex_{\text{biomass}} = \beta \text{LHV}_{\text{biomass}}, \quad (21)$$

where β is a coefficient given in terms of the ratios of oxygen-carbon and hydrogen-carbon as

$$\beta = \frac{1.0414 + 0.0177 \left[\frac{H}{C} \right] - 0.3328 \left[\frac{O}{C} \right] \left\{ 1 + 0.0537 \left[\frac{H}{C} \right] \right\}}{1 - 0.4021 \left[\frac{O}{C} \right]}. \quad (22)$$

The lower heating value of the biomass is

$$\text{LHV}_{\text{biomass}} = 0.0041868(1 + 0.15[O]) \left(7837.667[C] + 33888.889[H] - \frac{[O]}{8} \right), \quad (23)$$

where O , H , and C are the weight percentage of oxygen, hydrogen, and carbon elements in the biomass obtained from ultimate analysis. Tables 2 and 3 list the results of ultimate and proximate analyses, respectively. The higher heating value (HHV) can be obtained from the lower heating value of the biomass by using the correlation [29]

Table 1 Constant specific heat capacity of product constituents

Species	$c_p/(\text{kJ} \cdot \text{kmol}^{-1} \cdot \text{K}^{-1})$	Reference
H ₂	$c_p = 29.11 - 0.1916 \times 10^{-2}T + 0.4003 \times 10^{-5}T^2 - 0.870 \times 10^{-9}T^3$	[25]
CO	$c_p = 28.16 + 0.1675 \times 10^{-2}T + 0.5327 \times 10^{-5}T^2 - 2.22 \times 10^{-9}T^3$	[25]
CO ₂	$c_p = 22.26 + 5.981 \times 10^{-2}T - 3.501 \times 10^{-5}T^2 + 7.469 \times 10^{-9}T^3$	[25]
CH ₄	$c_p = 18.89 + 5.024 \times 10^{-2}T + 1.269 \times 10^{-5}T^2 - 11.01 \times 10^{-9}T^3$	[25]
N ₂	$c_p = 39.060 - 512.79 \left(\frac{T}{100}\right)^{-1.5} + 1072.7 \left(\frac{T}{100}\right)^{-2} - 820.4 \left(\frac{T}{100}\right)^{-3}$	[26]
O ₂	$c_p = 25.48 + 1.52 \times 10^{-2}T - 0.7155 \times 10^{-5}T^2 + 1.312 \times 10^{-9}T^3$	[25]
H ₂ O (g)	$c_p = 32.24 + 0.1932 \times 10^{-2}T + 1.055 \times 10^{-5}T^2 - 3.595 \times 10^{-9}T^3$	[25]
C	$c_p = 17.166 + 4.271 \frac{T}{1000} - \frac{8.79 \times 10^5}{T^2}$	[27]
C ₆ H ₆	$c_p = -36.22 + 48.475 \times 10^{-2}T - 31.57 \times 3.501 \times 10^{-5}T^2 + 77.62 \times 10^{-9}T^3$	[25]

Table 2 Proximate analysis results of biomass samples [24]

Feed stock	FC /wt. %	VM /wt. %	M /wt. %	A /wt. %
Rice husk	12	58	12	18
Coconut shell	17	71	8	4
Sawdust	16	76	7	1
Coir pith	20	57	10	13
Rubber seed shell	24	51	11	14

Table 3 Ultimate analysis results of biomass samples [24]

Feed stock	N /wt. %	C /wt. %	S /wt. %	H /wt. %	O /wt. %
Rice husk	2.43	34.35	0.31	5.22	57.66
Coconut shell	0.26	45.61	0.34	5.61	48.16
Sawdust	0.19	46.46	0	5.82	47.51
Coir pith	0.60	44.08	0	4.09	51.21
Rubber seed shell	2.13	41.11	0.27	6.60	49.88

$$\text{HHV} = \text{LHV} + 21.978H, \quad (24)$$

where H is the weight fraction of hydrogen in the biomass. LHV, HHV, β , and the exergy of different feedstocks are tabulated in Table 4. The chemical exergy of the gas mixture is [7]

Table 4 β , LHV, HHV and exergy of fuels

Biomass	β	LHV/(MJ·kg ⁻¹)	HHV/(MJ·kg ⁻¹)	$\dot{E}x_{\text{biomass}}/(\text{MJ} \cdot \text{kg}^{-1})$
Rice husk	1.48	18.02	19.17	26.66
Coconut shell	1.20	18.85	20.09	22.60
Sawdust	1.19	19.10	20.38	22.73
Coir pith	1.23	17.60	18.49	21.61
Rubber seed shell	1.24	19.39	20.84	24.11

$$\text{Ex}_{\text{chemical}} = \sum_i X_i \text{Ex}_{0,i} + RT_0 \sum_i X_i \ln X_i, \quad (25)$$

where X_i is the mole fraction of component i and Ex_0 is the standard chemical exergy for different constituents as summarized in Table 5.

Table 5 Standard chemical exergy for different components [25,30]

Component	Standard chemical exergy/(kJ·kmol ⁻¹)	Component	Standard chemical exergy/(kJ·kmol ⁻¹)
H ₂	236100	H ₂ O (gas)	9500
CO	275100	N ₂	720
CO ₂	19870	C	410260
CH ₄	831650	C ₆ H ₆	3303600

This paper evaluates the exergetic performance of the gasification system through three exergetic efficiencies, η_{Ex1} , η_{Ex2} and η_{Ex3} , which are defined as [8]

Exergy efficiency of hydrogen

$$\eta_{\text{Ex1}} = \frac{\dot{E}x_{\text{H}_2}}{\dot{E}x_{\text{biomass}} + \dot{E}x_{\text{steam}}}. \quad (26)$$

The exergy efficiency of product gas

$$\eta_{\text{Ex2}} = \frac{\dot{E}x_{\text{gas}}}{\dot{E}x_{\text{biomass}} + \dot{E}x_{\text{steam}}}. \quad (27)$$

The exergy efficiency of all the gasification products

$$\eta_{\text{Ex3}} = \frac{\dot{E}x_{\text{gas}} + \dot{E}x_{\text{char}} + \dot{E}x_{\text{tar}}}{\dot{E}x_{\text{biomass}} + \dot{E}x_{\text{steam}}}. \quad (28)$$

The exergy efficiency of the lost part

$$\eta_{\text{loss}} = 1 - \eta_{\text{Ex3}}, \quad (29)$$

where $\dot{E}x_{\text{H}_2}$, $\dot{E}x_{\text{gas}}$, $\dot{E}x_{\text{char}}$, $\dot{E}x_{\text{tar}}$, $\dot{E}x_{\text{biomass}}$ and $\dot{E}x_{\text{steam}}$ are the

exergy flow rates of hydrogen, product gases, char, tar, biomass and steam, respectively.

The entropy generation associated with the process

$$S_{\text{gen}} = \frac{I}{T_0}. \quad (30)$$

5 Model analysis

The developed quasi-steady-state model is used to predict the gasification performance of different biomasses through energy and exergy analyses. The influence of variables such as steam to biomass ratio (SBR), gasification temperature and equivalence ratio (ER) on energy and exergy efficiencies is studied.

6 Results and discussion

6.1 Influence of temperature, ER and SBR on energy efficiency

The effect of temperature on energy efficiency is depicted in Fig. 1(a). It is found that the energy efficiency increases with the increase in gasification temperature. This results from the increase in gas yield and the corresponding increase in the lower heating value of syngas at higher temperatures. From Fig. 1(b) it is observed that ER has an adverse effect on energy efficiency. This is attributed to the reduction of lower heating value of syngas as the gasification process shifts more toward combustion at higher ER values [31].

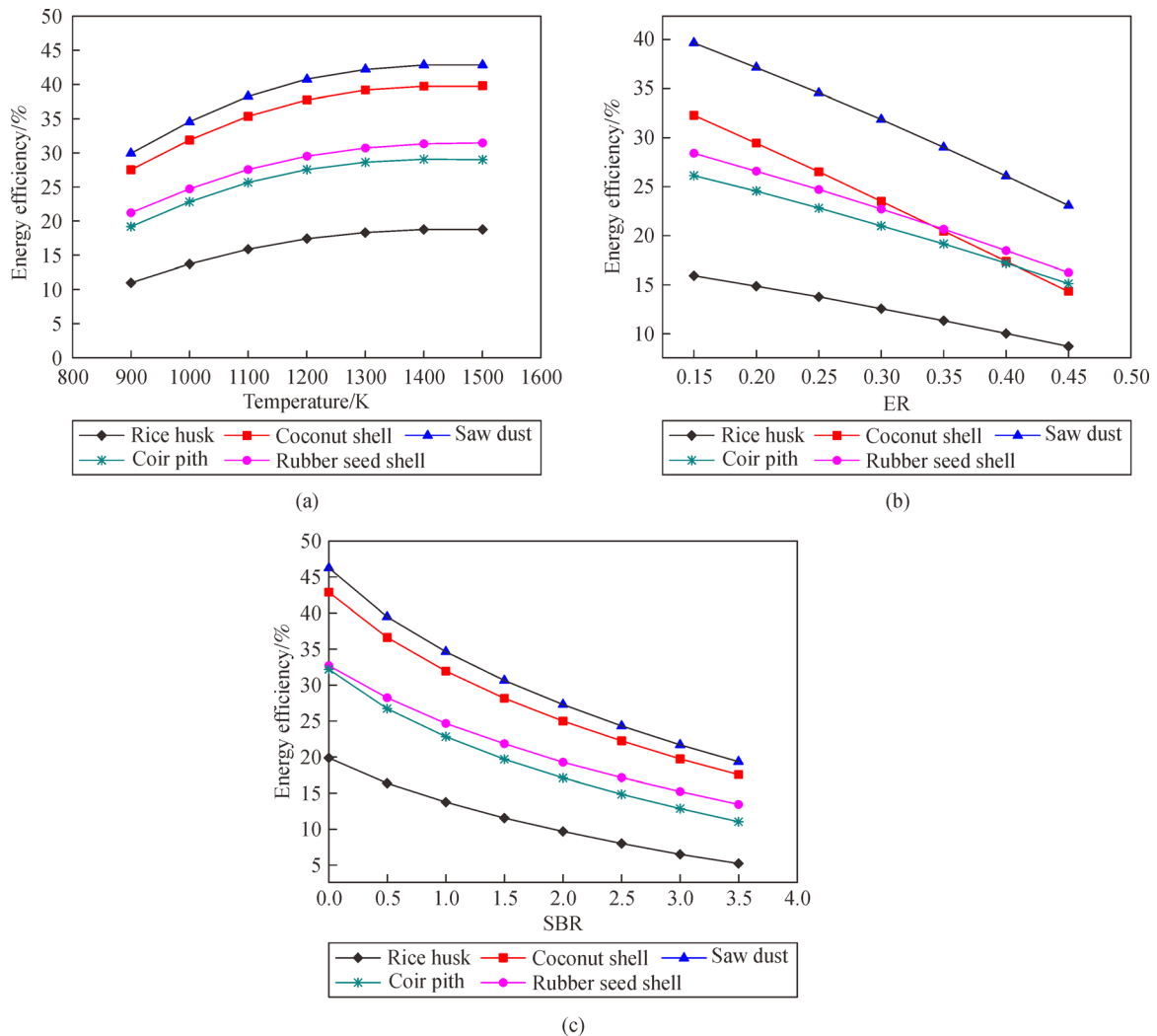


Fig. 1 Effect of operating parameters on energy efficiency

(a) Temperature (SBR = 1, ER = 0.25); (b) ER (SBR = 1, $T = 1000$ K); (c) SBR (ER = 0.25, $T = 1000$ K)

6.2 Exergy distribution of product gas

During gasification, the exergy present in the biomass is converted into the physical and chemical exergies of the product gas, and a portion of it is lost due to process irreversibilities. The chemical and physical exergy distribution of product gas for different feedstocks at different temperatures and SBRs are illustrated in Figs. 2 and 3, respectively. The physical exergy values of the product gas are found to be small compared to its chemical exergy values, which is in accordance with the observations made by Bhattacharya et al. [10] and Ptasiński et al. [32]. Specifically, the physical exergy values are 9.45%–25.78% lower than the corresponding chemical exergy values. This is attributed to the fact that product gases have much higher heating values than the corresponding temperature dependent enthalpy values [17]. The chemical exergy is found to be decreasing with SBR as steam addition is exergetically unfavorable. The exergy efficiency indicates the ratio between the exergy of useful gasification products and the feedstock exergy, whereas irreversibility indicates the amount of feedstock exergy being lost in gasification. Thus, different feedstocks can be compared based on the

process irreversibility or the degree of utilization of their chemical exergy [33]. The average irreversibility of the biomasses is calculated in the investigated regimes of temperature, SBR and ER, and is shown in Fig. 4. The irreversibility is maximum for rice husk and minimum for sawdust. It is also found that the biomass with the highest ash content contributes to maximum energy and exergy efficiencies, which is analogous to the observation made by Zhang et al. [17].

6.3 Influence of temperature, ER and SBR on exergy efficiencies

The effect of temperature on different exergy efficiencies is demonstrated in Fig. 5. It is observed that sawdust has the maximum value for all the exergy efficiencies, in the entire temperature range. The efficiency, η_{Ex1} is found to be increasing with temperature up to 1300 K and remains more or less constant thereafter. An increase of η_{Ex2} and η_{Ex3} with temperature is noticed for all the biomasses due to the increase in gas yield with reactor temperature.

The variation of exergy efficiencies with ER is portrayed in Fig. 6. All the exergy efficiencies are found to be

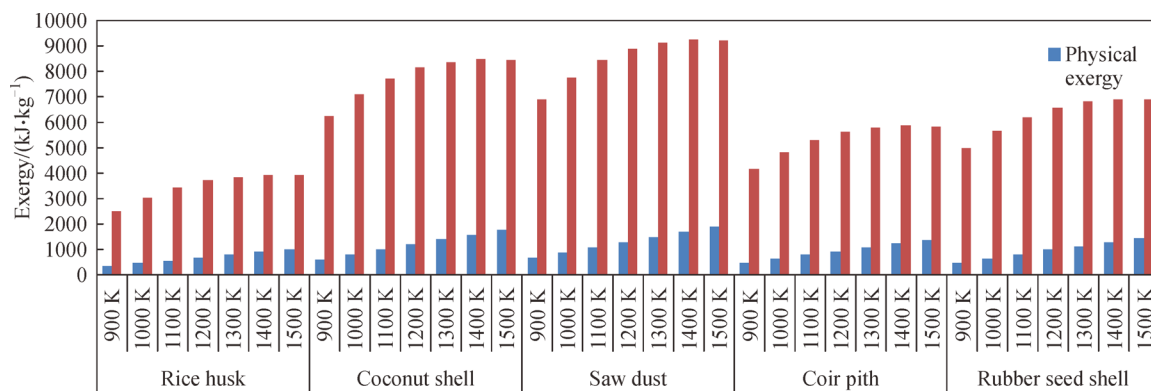


Fig. 2 Exergy distribution of product gas (SBR = 1, ER = 0.25)

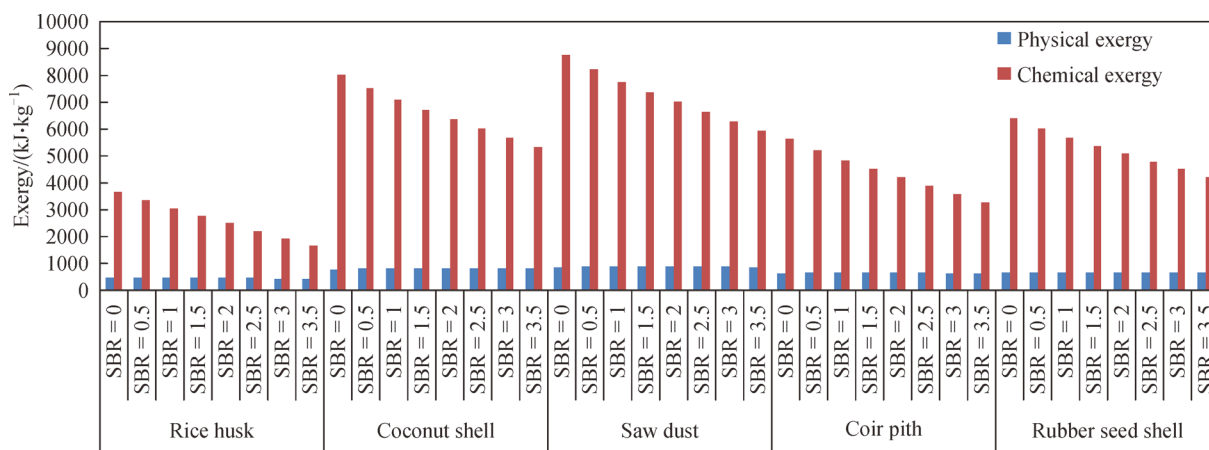


Fig. 3 Exergy distribution of product gas ($T = 1000$ K, ER = 0.25)

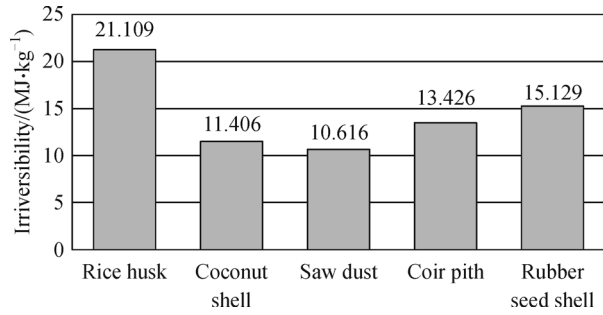


Fig. 4 Exergy destruction in gasification

decreasing with ER which is attributed to the shifting of the process from gasification to combustion due to increased air supply. This leads to a reduction in efficiencies as the specific exergy values of combustion products are less

compared to that of gasification products. The decreasing of exergy efficiencies with ER is in agreement with the decreasing reported by Hosseini et al. [12].

The effect of SBR on exergy efficiencies is displayed in Fig. 7. The exergy efficiency based on hydrogen is found to be increasing with SBR up to a value of 2 for all biomasses except for rice husk. This increase in η_{Ex1} with the increase in SBR is caused by the increase in hydrogen generation resulted from water gas shift reaction. From Fig. 7(a) and 7(b), it is observed that the exergy efficiencies η_{Ex2} and η_{Ex3} are decreasing with SBR, with a slightly lower rate of decrease for the latter one. The decrease in exergy efficiencies η_{Ex2} and η_{Ex3} is caused by the decrease in the lower heating value of the syngas with SBR. The lower rate of the decrease observed for η_{Ex3} is caused by the increase in exergy of tar content with steam, which is lower compared to the decrease in LHV with SBR.

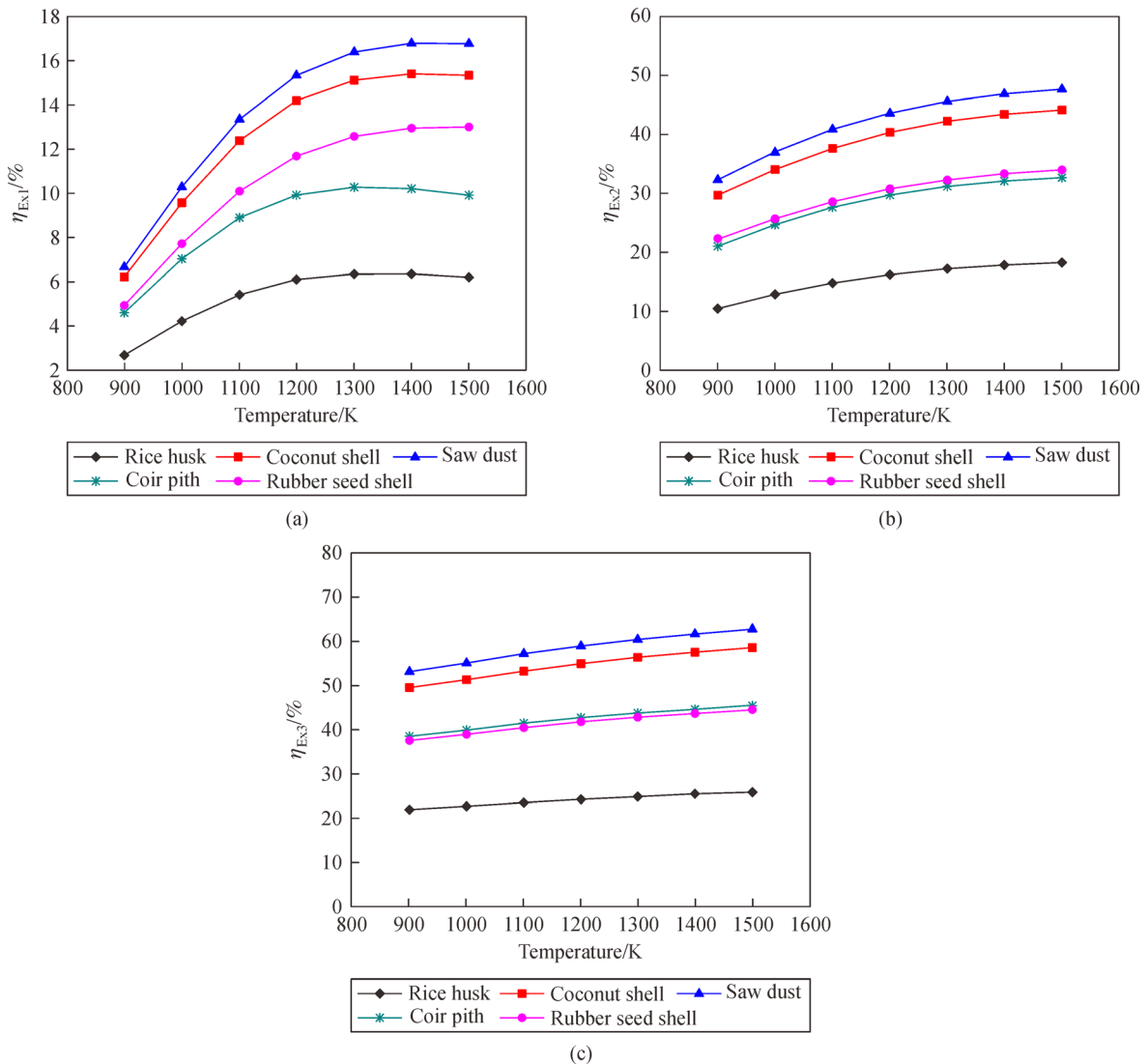


Fig. 5 Effect of temperature on exergy efficiencies

(a) η_{Ex1} (SBR = 1, ER = 0.25); (b) η_{Ex2} (SBR = 1, ER = 0.25); (c) η_{Ex3} (SBR = 1, ER = 0.25)

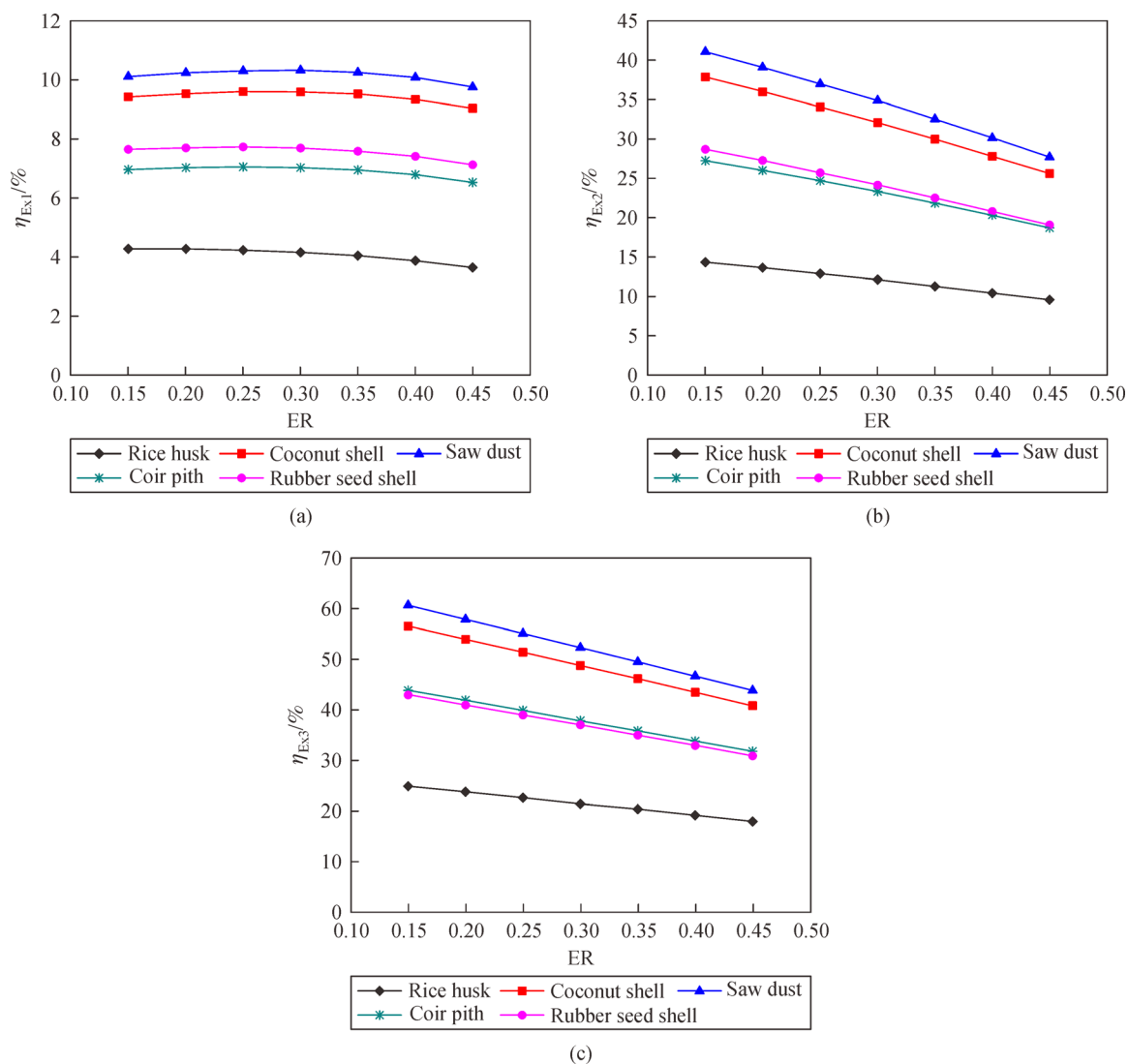


Fig. 6 Effect of ER on exergy efficiency
(a) η_{Ex1} (SBR = 1, $T = 1000$ K); (b) η_{Ex2} (SBR = 1, $T = 1000$ K); (c) η_{Ex3} (SBR = 1, $T = 1000$ K)

6.4 Influence of temperature, ER and SBR on entropy generation

The irreversibility associated with a gasification system is mainly caused by the chemical reaction and heat transfer. As the gasifier is considered as an adiabatic system in this model, the irreversibility and related entropy generation are only caused by the chemical reaction. The effect of temperature, ER and SBR on entropy generation is exhibited in Fig. 8.

Irreversibility is proportional to the difference between the exergy of reactants and products. As mentioned in Section 6.1, an increase in gasification temperature increases gas yield of the products which in turn increases the exergy of the products. Consequently, the entropy generation experiences a decrease with temperature. Similarly, the decrease in exergy of the products with ER and the increase in exergy of the reactants with SBR are the

reasons for the increase in entropy generation with ER and SBR. The variations of entropy generation with temperature and SBR respectively are similar to the observations reported by Sreejith et al. [33].

6.5 Comparison of energy and exergy efficiencies

Table 6 provides a comparison of energy and exergy efficiencies for different biomass materials. It is evident from Table 6 that the exergy efficiency is greater than the energy efficiency for all the biomasses except rice husk. Exergy efficiency was reported as higher to the corresponding energy efficiency by Ptasinski et al. [32], and Zhang et al. [17] whereas the reverse trend was observed by Abuadala et al. [7] and Abuadala and Dincer [8]. It depends on the relative magnitudes of the ratios of output energy in the product gas to the total energy input to the gasifier, and the exergy of the gaseous products to the total

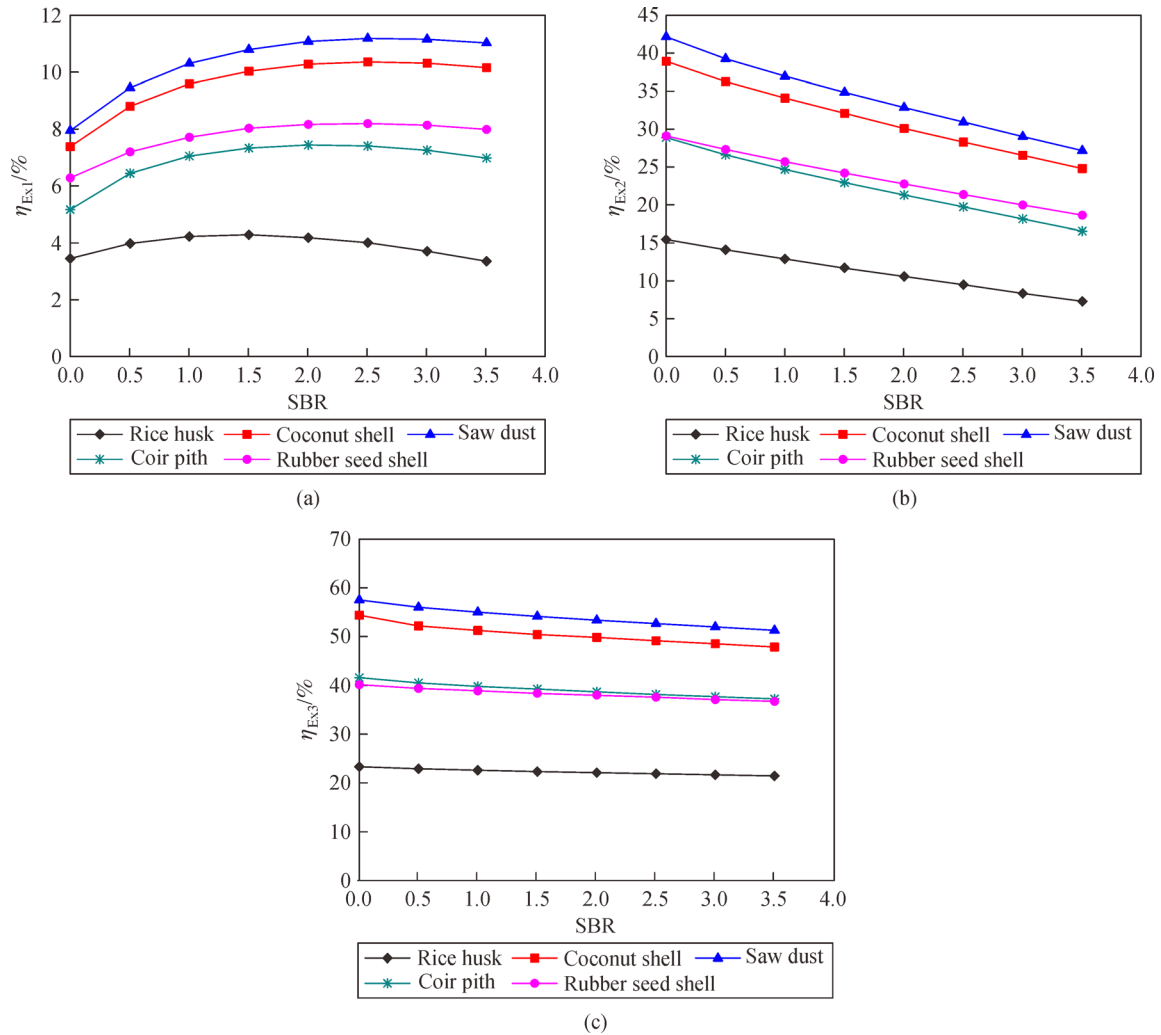


Fig. 7 Effect of SBR on exergy efficiency
(a) η_{Ex1} (ER = 0.25, $T = 1000$ K); (b) η_{Ex2} (ER = 0.25, $T = 1000$ K); (c) η_{Ex3} (ER = 0.25, $T = 1000$ K)

exergy of the input stream. The total exergy of the input stream depends on the exergy of the biomass. From Table 4, it is clearly seen that rice husk is the biomass which has the highest exergy and hence the magnitude of exergy efficiency for rice husk is lower compared to other feedstocks.

The exergy efficiency, η_{Ex3} has a larger value than η_{Ex1} and η_{Ex2} for all the biomasses considered because it accounts all the gasification products. A comparison of exergy efficiencies for different biomasses is given in Table 7. Sawdust and rice husk are found to have the highest and the lowest exergetic efficiencies, respectively over the entire temperature range considered.

7 Regression analysis

A regression analysis is performed using statistical software Minitab 16 and correlations for parameters like

energy efficiency, exergy efficiency and LHV of syngas are formulated in terms of gasification temperature, SBR and ER. Each parameter is considered for the entire ranges of temperature, SBR and ER and the resulted 392 values for each parameter are used for formulating the regression equations. The regression equations for the energy and exergy efficiencies and LHV of syngas are presented in Table 8.

8 Conclusions

A quasi-steady-state model was developed to simulate the biomass gasification process considering char conversion and tar formation. The developed model was used to evaluate and compare the performance of locally available biomass materials in the Indian subcontinent like rice husk, sawdust, coconut shell, coir pith and rubber seed shell during gasification. The energy and exergy analyses were

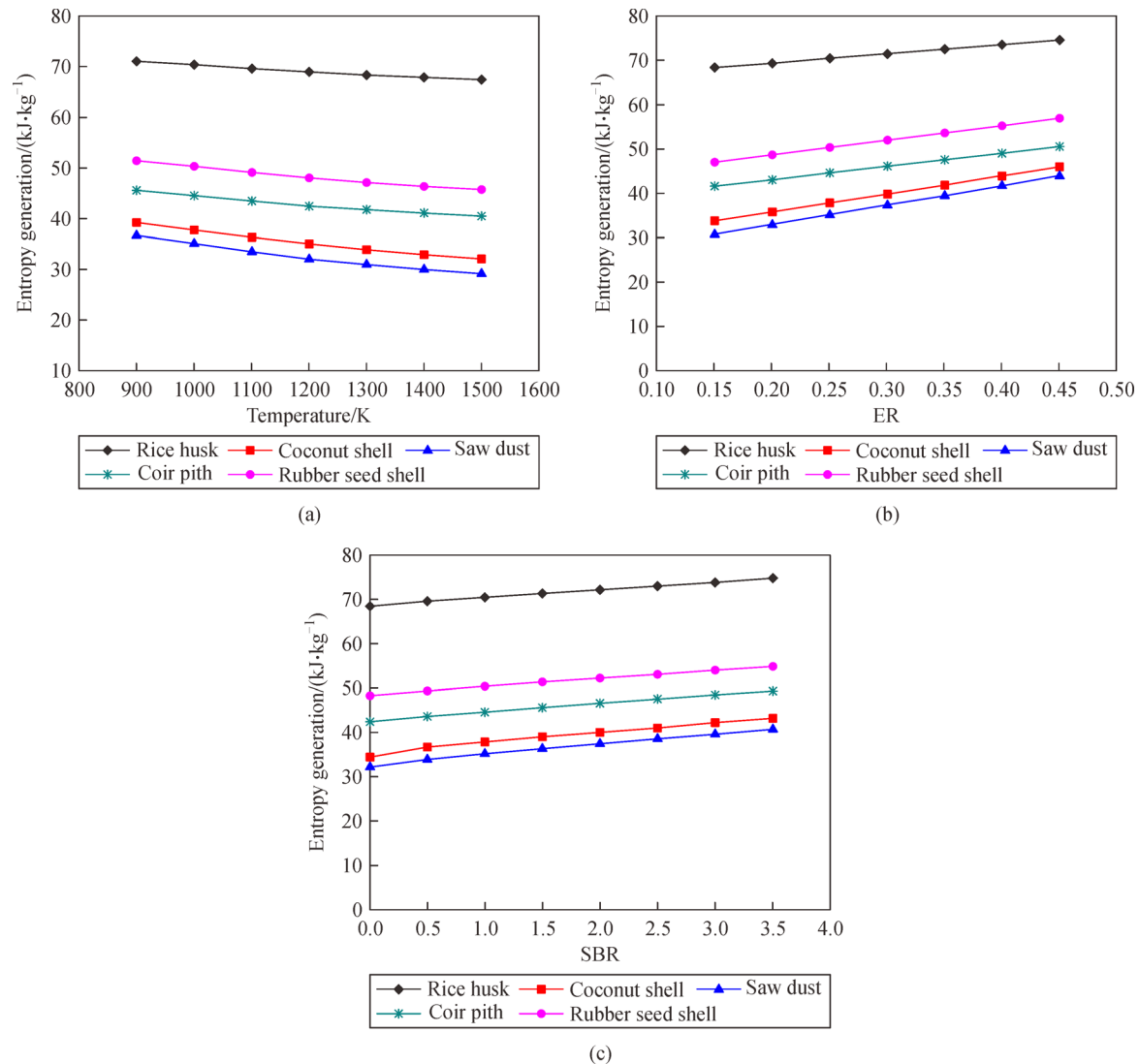


Fig. 8 Effect of operating parameters on entropy generation
(a) Temperature (SBR = 1, ER = 0.25); (b) ER (SBR = 1, $T = 1000$ K); (c) SBR (ER = 0.25, $T = 1000$ K)

Table 6 Effect of temperature on energy and exergy efficiencies (SBR = 1, ER = 0.25)

Biomass	Efficiency	Temperature/K			
		900	1100	1300	1500
Rice husk	Energy/%	11.82	17.12	19.71	20.23
	Exergy (η_{Ex2}) /%	10.50	14.82	17.24	18.31
Coconut shell	Energy/%	28.51	36.65	40.57	41.28
	Exergy (η_{Ex2}) /%	29.68	37.67	42.19	44.16
Sawdust	Energy/%	30.88	39.43	43.56	44.31
	Exergy (η_{Ex2}) /%	32.32	40.78	45.58	47.70
Coir pith	Energy/%	20.17	27.03	30.15	30.57
	Exergy (η_{Ex2}) /%	21.06	27.64	31.20	32.65
Rubber seed shell	Energy/%	22.49	29.18	32.58	33.37
	Exergy (η_{Ex2}) /%	22.25	28.59	32.29	34.02

Table 7 Comparison of different exergy efficiencies for different biomasses (SBR = 1, ER = 0.25)

Biomass	Exergy efficiency	Temperature/K						
		900	1000	1100	1200	1300	1400	1500
Rice husk	$\eta_{Ex1}/\%$	2.70	4.24	5.44	6.12	6.38	6.37	6.21
	$\eta_{Ex2}/\%$	10.51	12.91	14.82	16.24	17.23	17.89	18.31
	$\eta_{Ex3}/\%$	21.86	22.65	23.48	24.23	24.86	25.40	25.86
Coconut shell	$\eta_{Ex1}/\%$	6.23	9.60	12.39	14.19	15.11	15.41	15.34
	$\eta_{Ex2}/\%$	29.68	34.09	37.67	40.34	42.19	43.41	44.17
	$\eta_{Ex3}/\%$	49.50	51.36	53.28	54.97	56.37	57.52	58.52
Sawdust	$\eta_{Ex1}/\%$	6.70	10.32	13.35	15.35	16.39	16.78	16.75
	$\eta_{Ex2}/\%$	32.32	36.98	40.78	43.61	45.58	46.89	47.70
	$\eta_{Ex3}/\%$	53.13	55.12	57.19	59.00	60.50	61.74	62.81
Cair pith	$\eta_{Ex1}/\%$	4.63	7.06	8.91	9.93	10.28	10.22	9.93
	$\eta_{Ex2}/\%$	21.06	24.73	27.64	29.76	31.20	32.12	32.65
	$\eta_{Ex3}/\%$	38.44	39.89	41.38	42.67	43.72	44.60	45.36
Rubber seed shell	$\eta_{Ex1}/\%$	4.96	7.73	10.11	11.71	12.59	12.95	13.00
	$\eta_{Ex2}/\%$	22.25	25.73	28.59	30.75	32.29	33.34	34.02
	$\eta_{Ex3}/\%$	37.62	38.99	40.46	41.77	42.87	43.79	44.58

Table 8 Regression equations for energy and exergy efficiencies, and LHV of syngas

Sl. No.	Biomass	Regression equation/%	$R^2/\%$
1	Rice husk	$\eta_{Ex1} = -2.15 + 0.00616T - 2.77ER + 0.438 \text{ SBR}$	80.1
		$\eta_{Ex2} = 1.49 + 0.0154T - 11.8ER - 1.64 \text{ SBR}$	91.2
		$\eta_{Ex3} = 21.8 + 0.00684T - 21.9ER - 0.508 \text{ SBR}$	99.6
		$\eta_{En} = 8.09 + 0.0157T - 23.6ER - 3.32 \text{ SBR}$	93.3
		$\text{LHV} = 1.08 + 0.00332T - 4.72ER - 0.420 \text{ SBR}$	89.8
2	Coconut shell	$\eta_{Ex1} = -5.98 + 0.0158T - 8.29ER + 1.16 \text{ SBR}$	80.4
		$\eta_{Ex2} = 14.8 + 0.0291T - 32.0ER - 2.96 \text{ SBR}$	92.9
		$\eta_{Ex3} = 51.2 + 0.0145T - 50.0ER - 1.49 \text{ SBR}$	98
		$\eta_{En} = 29.9 + 0.0205T - 44.8ER - 5.61 \text{ SBR}$	88.3
		$\text{LHV} = 4.52 + 0.00538T - 10.2ER - 0.570 \text{ SBR}$	92.1
3	Sawdust	$\eta_{Ex1} = -6.64 + 0.0172T - 9.03ER + 1.26 \text{ SBR}$	81.3
		$\eta_{Ex2} = 16.9 + 0.0308T - 35.0ER - 3.15 \text{ SBR}$	93.1
		$\eta_{Ex3} = 54.2 + 0.0162T - 53.9ER - 1.62 \text{ SBR}$	99.6
		$\eta_{En} = 19.6 + 0.0274T - 44.7ER - 3.99 \text{ SBR}$	84.9
		$\text{LHV} = 5.09 + 0.00574T - 11.2ER - 0.600 \text{ SBR}$	92.3
4	Cair pith	$\eta_{Ex1} = -3.634 + 0.01094T - 5.471ER + 0.562 \text{ SBR}$	79.6
		$\eta_{Ex2} = 5.94 + 0.0250T - 20.9ER - 2.44 \text{ SBR}$	92.2
		$\eta_{Ex3} = 38.7 + 0.0118T - 38.1ER - 1.04 \text{ SBR}$	99.6
		$\eta_{En} = 14.8 + 0.0205T - 32.1ER - 4.14 \text{ SBR}$	94.1
		$\text{LHV} = 2.18 + 0.00444T - 6.83ER - 0.469 \text{ SBR}$	91.3
5	Rubber seed shell	$\eta_{Ex1} = -5.51 + 0.0139T - 7.39ER + 0.756 \text{ SBR}$	83.3
		$\eta_{Ex2} = 9.74 + 0.0237T - 25.7ER - 2.18 \text{ SBR}$	93.2
		$\eta_{Ex3} = 37.9 + 0.0118T - 38.5ER - 0.897 \text{ SBR}$	99.7
		$\eta_{En} = 19.3 + 0.0202T - 37.9ER - 4.13 \text{ SBR}$	95.1
		$\text{LHV} = 3.35 + 0.00464T - 8.51ER - 0.460 \text{ SBR}$	92.6

the tools used to compare the gasification performance of the selected biomasses. The effect of key operating parameters such as reactor temperature, ER and SBR on energy efficiency, exergy efficiency and entropy generation was analyzed. Of the biomass materials, rice husk has the highest chemical exergy, followed by rubber seed shell, sawdust, coconut shell, and coir pith, whereas sawdust has the highest total exergy content of gas mixture, followed by coconut shell, rubber seed shell, coir pith, and rice husk. The average irreversibility is found to be maximum for rice husk (21.11 MJ/kg) and minimum for sawdust (10.62 MJ/kg). Thus, it is inferred that sawdust to syngas conversion is exergetically the more efficient among the biomasses considered, with higher energy and exergy efficiencies of 35.62% and 36.98%, respectively at a gasification temperature of 1000 K, and a steam to biomass ratio of unity and equivalence ratio of 0.25. Thus the developed model is an effective tool in feedstock selection, for biomass air-steam gasification, by predicting and comparing the gasification performance of different feedstocks in terms of energy and exergy efficiencies.

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