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Review Paper

Exergy sustainability analysis of biomass gasification: a critical review

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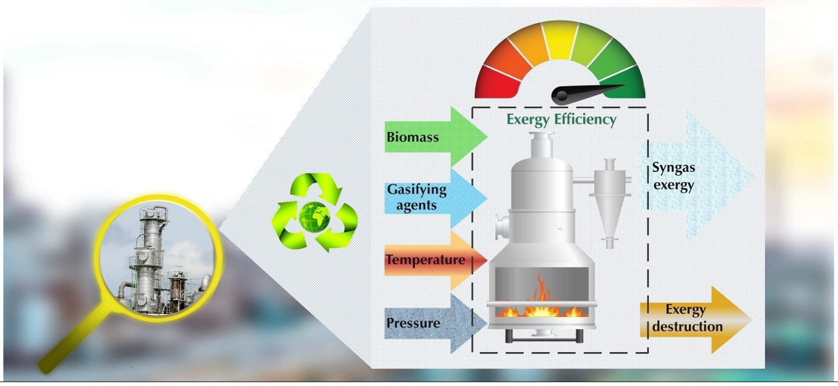
HIGHLIGHTS

- ➢The use of exergy methods for analyzing biomass gasification systems is critically reviewed.
- ➢Bibliometric analysis identifies research themes in the exergy analysis of biomass gasification.
- ➢Effects of process parameters on the exergy efficiency of biomass gasification are examined.
- ➢The highest exergy efficiency is observed for a blend of CO_2 and steam as a gasifying medium.
- ➢The downdraft fixed-bed gasifier exhibits the highest exergy efficiency among biomass gasifiers.

GRAPHICAL ABSTRACT



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ABSTRACT

Biomass gasification technology is a promising process to produce a stable gas with a wide range of applications, from direct use to the synthesis of value-added biochemicals and biofuels. Due to the high capital/operating costs of the technology and the necessity for prudent management of thermal energy exchanges in the biomass gasification process, it is important to use advanced sustainability metrics to ensure that environmental and other sustainability factors are addressed beneficially. Consequently, various engineering techniques are being used to make decisions on endogenous and exogenous parameters of biomass gasification processes to find the most efficient, viable, and sustainable operations and conditions. Among available approaches, exergy methods have attracted much attention due to their scientific rigor in accounting for the performance, cost, and environmental impact of biomass gasification systems. Therefore, this review is devoted to critically reviewing and numerically scrutinizing the use of exergy methods in analyzing biomass gasification systems. First, a bibliometric analysis is conducted to systematically identify research themes and trends in exergy-based sustainability assessments of biomass gasification systems. Then, the effects of biomass composition, reactor type, gasifying agent, and operating parameters on the exergy efficiency of the process are thoroughly investigated and mechanistically discussed. Unlike oxygen, nitrogen, and ash contents of biomass, the exergy efficiency of the gasification process is positively correlated with the carbon and hydrogen contents of biomass. A mixed gasifying medium (CO_2 and steam) provides higher exergy efficiency values. The downdraft fixed-bed gasifier exhibits the highest exergy efficiency among biomass gasification systems. Finally, opportunities and limitations of exergy methods for analyzing sustainability aspects of biomass gasification systems are outlined to guide future research in this domain.

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Contents

Nomenclature

A	Ash content (wt%)	$\dot{W}$	Work rate (kW)
c	Specific heat capacity (kJ/kg K)	x	Mass fraction (-)
C	Carbon content (wt%)	y	Mole fraction (-)
DP	Depletion number (-)	z	Height (m)
$\dot{E}$	Exergy rate (kW)	**Subscripts**	
ex	Specific exergy (kJ/kg)	0	Reference state
G	Gibbs free energy (kJ/mol)	a	Air
g	Gravitational acceleration constant (m^2/s)	d	Destruction
h	Specific enthalpy (kJ/kg)	e	Exit
H	Hydrogen content (wt%)	j, m, l	Numerators
$\dot{IP}$	Exergetic improvement potential rate (kW)	i	Inlet
LHV	Lower heating value (kJ/kg)	tot	Total
$\dot{m}$	Mass flow rate (kg/s)	v	Vapor
M	Molecular weight (kg/mol)	**Superscripts**	
n	Mole number	ph	Physical
N	Nitrogen content (wt%)	ch	Chemical
O	Oxygen content (wt%)	ke	Kinetic
P	Absolute pressure (kPa)	pe	Potential
$\dot{Q}$	Heat rate (kW)	**Greek symbols**	
R	Gas constant (kJ/kg K)	ω	Humidity ratio (-)
$\bar{R}$	Universal gas constant (8.314 kJ/mol K)	ε	Standard chemical exergy (kJ/mol)
s	Specific entropy (kJ/kg K)	β	Weighting factor (-)
S	Sulfur content (wt%)	ϕ	Universal exergy efficiency (%)
SI	Sustainability index (-)	ψ	Functional exergy efficiency (%)
T	Temperature (K)	**Abbreviations**	
V	Velocity (m/s)	sej	Solar emjoules

1. Introduction

Due to rapid population growth, industrialization, urbanization, and socio-economic development, global energy consumption is continuously rising. As shown in **Figure 1a**, global energy consumption is expected to increase from 634.58 exajoule in 2020 to 935.04 exajoule in 2050 based on the data released by Energy Information Administration (EIA, 2019). Currently, fossil fuels such as oil, coal, and natural gas are the most frequently employed energy sources worldwide (**Fig. 1b**) (BP, 2020). However, fossil reserves are dwindling and, more importantly, their utilization is directly linked to climate change and ecosystem degradation. The growing environmental and other concerns regarding the excessive use of fossil fuel resources have stimulated research on developing and utilizing renewable energy technologies. Among various renewable energy resources, biomass energy (bioenergy) has gained increasing acceptance worldwide due to its ubiquitous, versatile, and compatible nature. According to projections of the International Energy Agency, biomass contribution to the global energy supply portfolio is expected to be around 10% by 2035 (Mohapatra and Singh, 2021). In addition, biomass-derived fuels have the potential to provide around 27% of global transportation fuels by 2050 (Mohapatra and Singh, 2021).

Several conversion routes have been investigated to produce bioenergy from various biomass feedstocks, including thermochemical (such as combustion, pyrolysis, gasification, liquefaction, and torrefaction), biochemical (such as composting, anaerobic digestion, and fermentation), and chemical (such as transesterification and esterification). Biomass thermochemical conversion routes have attracted increasing interest in recent decades for bioenergy production owing to their numerous benefits such as fast conversion, feedstock flexibility, product diversity, and higher efficiency (Soltanian et al., 2020). More importantly, thermochemical conversion processes play a pivotal role in biomass-based biorefinery systems. Among thermochemical methods, the gasification process has proven to be a promising approach to convert biomass into a combustible gas (syngas), condensable compounds (tar), and solid residue (biochar) at temperatures in the range of 600–1500 °C under the presence of a gasifying agent (normally air, steam, O_2, CO_2). The syngas, consisting of H_2, CH_4, CO, and CO_2, can be further processed to produce heat and electricity in power generation systems, to generate liquid transportation biofuels via Fischer-Tropsch synthesis, and to synthesize a wide spectrum of biofuels/biochemicals through biological processes (Sikarwar et al., 2016; Soltanian et al., 2022).

Despite the efficient, renewable, and eco-friendly nature of biomass gasification, this process requires high investment and operating costs. Also, this exothermic process is carried out at high temperatures while producing large amounts of thermal energy. Therefore, the thermal energy generated and consumed by biomass gasification needs to be effectively managed in order to improve its sustainability. Furthermore, various factors, including reactor type/configuration, biomass composition, particle size, gasification temperature, gasifying agent, gasifying agent/biomass ratio, catalyst type and quantity, and residence time, affect the performance

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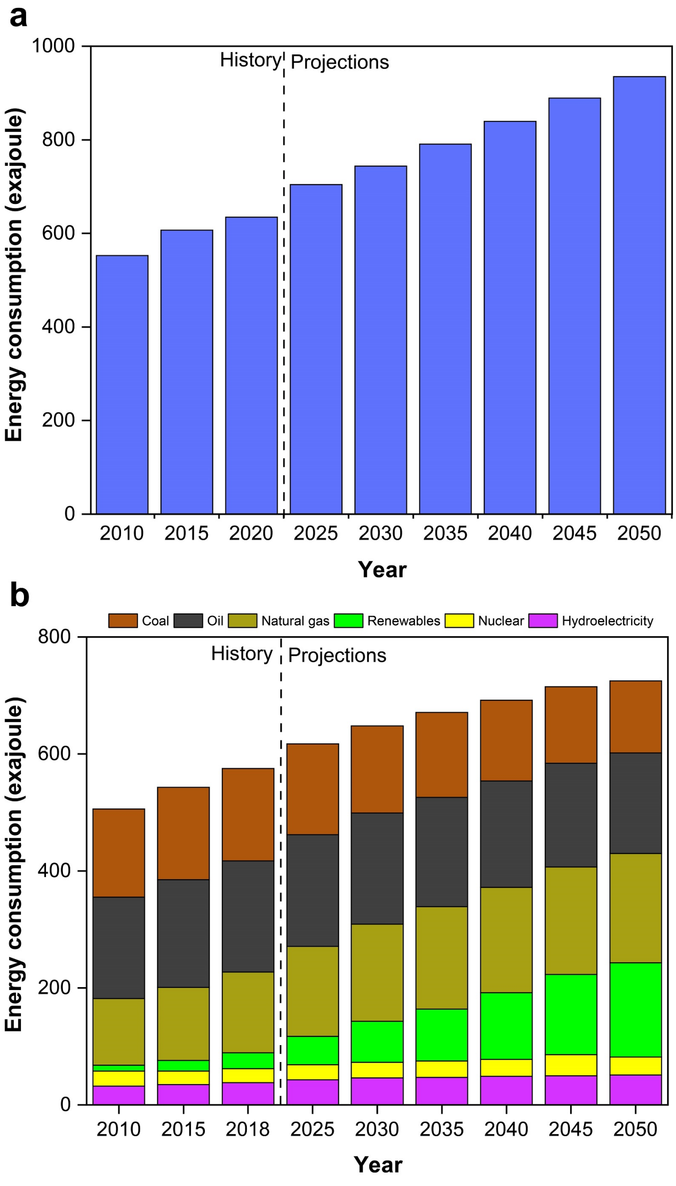

Fig. 1. **(a)** Global energy consumption outlook from 2010 to 2050 according to the Energy Information Administration (EIA, 2019) and **(b)** share of non-renewable and renewable energy sources to the global energy perspective from 2010 to 2050 according to British Petroleum (BP, 2020).

of the biomass gasification process (Zhang et al., 2019). Accordingly, there is a need for advanced sustainability assessment indicators for the biomass gasification process to ensure its sustainability and to avoid significant environmental impacts. Various engineering frameworks, including techno-economic analysis, thermodynamic-based measures (energy, emergy, and exergy-based approaches), and life cycle assessment, have been employed in past decades for measuring the sustainability aspects of biomass gasification technology.

Techno-economic analysis evaluates the economic feasibility and commercialization potential of a process by considering the total costs (capital and operating) and the potential incomes (Patel et al., 2016). Nevertheless, this sustainability assessment approach is not able to provide useful information concerning environmental and thermodynamic aspects of bioenergy systems (Cherp et al., 2018). Life cycle assessment is another useful tool to assess the potential environmental impacts (climate change, human health, ecosystem, and resource consumption) of bioenergy projects throughout their life cycles (Ubando et al., 2019). However, this method lacks a standard procedure to specify system boundaries and interpret the obtained results (Wunderlich et al., 2021). Emergy analysis evaluates the sustainability of bioenergy systems by translating their inputs (human labor, money, natural resource, and services) into solar energy equivalents known as solar emjoules (sej). Selection of the proper transformity values to express all flows is the most challenging step in conducting emergy analysis (Tabatabaei and Aghbashlo, 2020). Energy analysis, based on the first law of thermodynamics, is the most widely used approach in the energy assessment of bioenergy systems. Despite the commonality of energy analysis, it does not necessarily lead to reliable decision-making because it disregards energy quality.

The exergy concept and exergy methods stemming from it have attracted much attention among available approaches, in part because its scientific rigor provides an opportunity to account for resource use (Grubb and Bakshi, 2011). This promising methodology effectively resolves the shortcomings of energy analysis by simultaneously measuring the quality and quantity of energy flows (Reyes et al., 2021). Exergy can also fairly weigh the work potential of material flows. In simple terms, exergy quantifies the maximum useful work obtainable from an energy or material flow when it is brought to equilibrium with a reference state by reversible processes (Aghbashlo and Rosen, 2018a). By conducting exergy analysis, the location, quantity, and source of thermodynamic inefficiencies (exergy destructions and losses) of bioenergy systems can be determined (Mahian et al., 2020). Given the direct relationship between resource conservation/depletion and exergy destruction (as shown in **Figure 2**), exergy analysis can reliably measure the viability and sustainability of bioenergy systems. Additionally, the exergy concept can be extended by integrating it with economic and environmental factors and constraints (Aghbashlo and Rosen, 2018b).

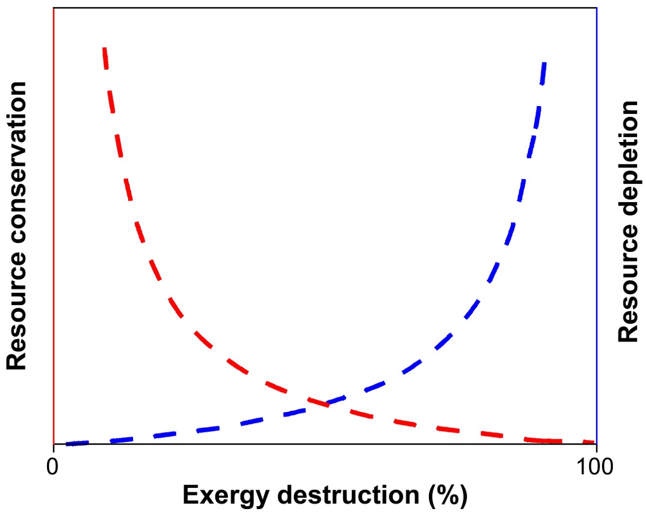

Fig. 2. The relationship between resource conservation and resource depletion with its exergy destruction. Adopted from Soltanian et al. (2022).

Due to the appealing features of the exergy concept, it has been increasingly used by researchers to assess the sustainability aspects of biomass gasification technology. The present review aims to critically review and numerically scrutinize the use of exergy analysis in investigating biomass gasification systems. In addition, a bibliometric analysis is conducted to systematically identify research themes and trends in exergy-based sustainability assessments of biomass gasification systems. To the best of the authors' knowledge, no comprehensive review has been reported on the advancement of and existing issues associated with applying exergy analysis to biomass gasification systems. **Table 1** summarizes the key review papers dealing with exergy analysis of biomass gasification systems and points out the topics covered, further highlighting the originality of the present review.

Table 1.
Key review papers dealing with exergy analysis of biomass gasification systems.

Reference	Exergy analysis	Bibliometric analysis	Data visualization	Effect of operating conditions	Reactor type/configuration	Integration of gasification with other processes
Chen et al. (2020)	✓	✗	✗	✗	✓	✗
Ptasinski (2008)	✓	✗	✗	✓	✗	✓
Christopher and Dimitrios (2012)	✓	✗	✗	✗	✗	✗
Abuadala and Dincer (2012)	✓	✗	✗	✗	✗	✗
Ibrahim et al. (2018)	✓	✗	✗	✓	✗	✓
Kalinci et al. (2009)	✓	✗	✗	✓	✓	✗
Present review	✓	✓	✓	✓	✓	✗

2. Bibliometric analysis

Bibliometric analysis is a robust statistical method to quantitatively assess the relevant academic literature to identify the main research (i.e., research hotspots and trends) (Du et al., 2021; Ranjbari et al., 2022). To utilize this useful tool, an important step involves defining a suitable search protocol to obtain as many relevant papers as possible. In this regard, the following search string was designed here: ("gasification" AND "biomass" AND "exergy") AND ("synthetic gas" OR "syngas" OR "thermodynamics" OR "second law of thermodynamics" OR "irreversibility" OR "exergy destruction" OR "thermochemical conversion" OR "exergetic" OR "exergy efficiency"). The primary run of the search string within the article titles, abstracts, and keywords of the literature in the Scopus database returned 488 articles. To increase the reliability of the analysis, exclusion criteria were considered. Therefore, only peer-reviewed journal articles in English with no time-period limit were considered. This constraint led to a total of 375 articles remaining for further processing. In the next step, the remaining papers were completely screened based on their titles and abstracts to ensure the quality of the studied sample. As a result, a total of 365 eligible articles were selected for the bibliometric analysis. VOSviewer software (version 1.6.18) was employed to conduct the bibliometric analysis (van Eck and Waltman, 2010). The procedures for selecting and collecting articles are detailed in **Table 2**. **Figure 3** displays the publication trend of exergy-based sustainability assessments of biomass gasification systems from 2005 to 2021. The number of studies using exergy for analyzing biomass gasification systems is observed to have grown significantly over that time period, especially in the last few years.

Table 2.
Procedures for selecting and collecting articles.

Step	Description
Search string	"gasification" AND "biomass" AND "exergy" AND "synthetic gas" OR "syngas" OR "thermodynamics" OR "second law of thermodynamics" OR "irreversibility" OR "exergy destruction" OR "thermochemical conversion" OR "exergetic" OR "exergy efficiency"
Database	Scopus
Search within	Article titles, abstracts, and keywords
Date of search	January 29, 2022
Limitation in the year of publications	No
Inclusion criteria	Peer-reviewed journal articles in the English language
Initial Result	488 articles
Exclusion criteria	Book chapter, conference papers, editorial, note, letters, erratum, and non-English documents
Second result	375 articles
Screening stage	10 articles were removed
Eligible article	365 articles

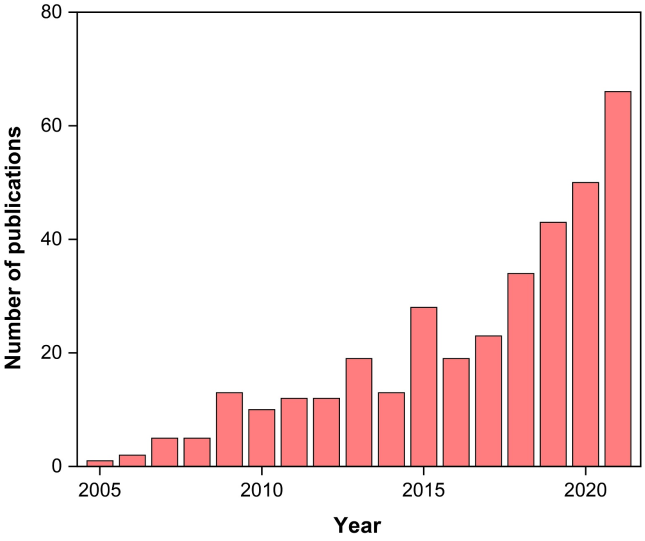

Fig. 3. Publication trend of exergy-based sustainability assessments of biomass gasification systems from 2005 to 2021.

Keyword co-occurrence analysis was performed based on the keywords provided by authors, which could effectively express the field and main idea of each research. This method helps identify research hotspots and frontiers within the context of the selected domain (Det Udomsap and Hallinger, 2020). Some amendments were conducted in keywords before analysis: (i) replacing the short form (abbreviations) of the terms with their full forms where applicable, (ii) merging singular and plural formats of the keywords, (iii) unifying writing style, and (vi) eliminating general words without clear meaning such as "article" and "literature review". Accordingly, the top 15 most frequent keywords (among 456 keywords within the database) are tabulated in **Table 3**. As can be seen, exergy analysis, gasification, and biomass are the three most frequently used keywords of the authors, with 164, 164, and 162 occurrences, respectively. The large difference between the total link strength (i.e., the total connection of the links each keyword has with others) of these three most prominent keywords and other items highlights the attractiveness of exergy sustainability analysis of biomass gasification system among researchers. The next most frequent keywords in exergy-based sustainability analysis of biomass gasification are as follows: gasifier, hydrogen, energy analysis, solid oxide fuel cell, exergoeconomic analysis, multi-objective optimization, and syngas. The focus of these keywords in the selected domain is on the gasifier (as the main part of the biomass gasification process), product type (i.e., hydrogen or syngas), and economic assessment of the system.

The bibliographic coupling clustering technique was performed based on the reference numbers that each article cited to define a reliable map of

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Table 3.
Top 15 most frequently occurring keywords in the eligible articles.

Keyword	Total link	Total link strength	Occurrences
Exergy analysis	124	681	164
Gasification	124	677	164
Biomass	125	702	162
Gasifier	84	250	64
Hydrogen	80	268	59
Energy analysis	59	242	51
Solid oxide fuel cell	61	195	47
Exergoeconomic analysis	52	191	44
Multi-objective optimization	58	157	37
Syngas	63	152	36
Exergy efficiency	50	119	34
Combined heat and power	40	105	25
Irreversibility	42	91	23
Carbon capture	40	79	21
Solar energy	36	67	17

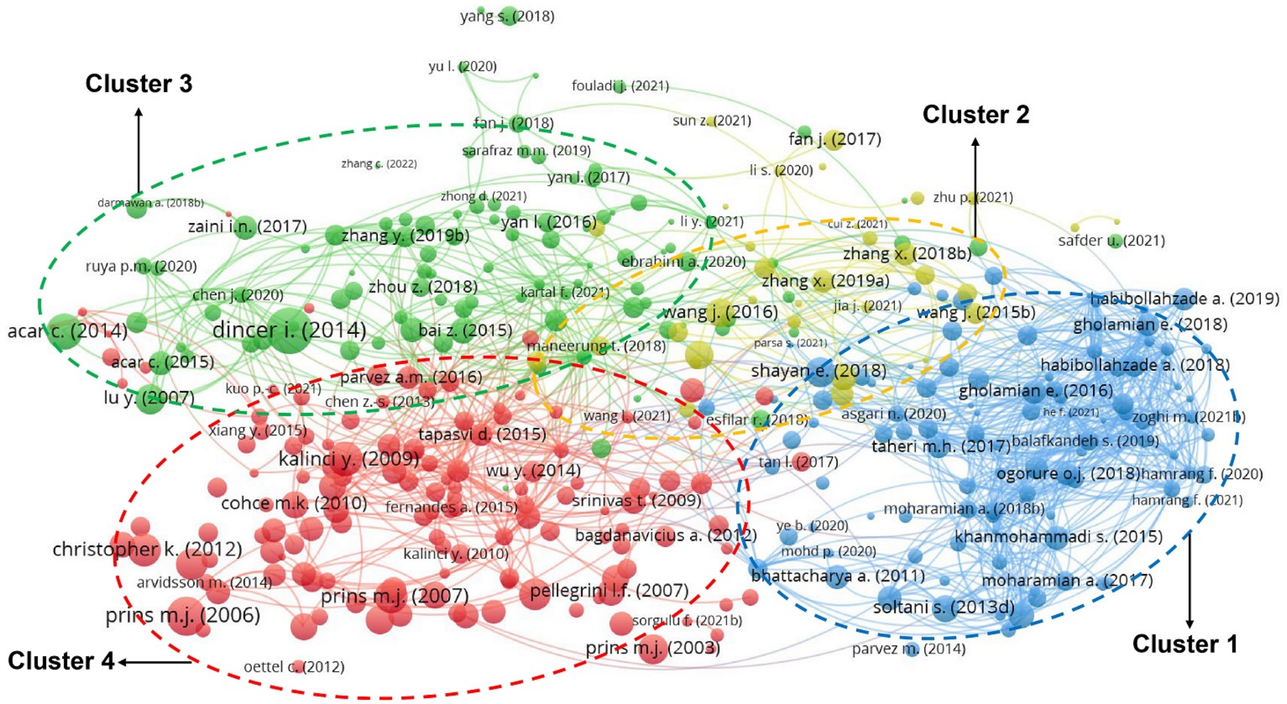
the emergent research themes in the domain (Ranjbari et al., 2021). As shown in **Figure 4**, the four major research hotspots constituting the research field of exergy sustainability analysis of biomass gasification systems based on 375 articles were identified as follows: (1) integrating solid oxide fuel cell/organic Rankine cycle with biomass gasification systems and using exergy analysis and its extensions for their analysis, (2) thermodynamic analysis of biomass gasification systems consolidated with combined heat and power and combined cooling, heating, and power plants, (3) sustainability aspects analysis of hydrogen production from biomass gasification, and (4) effect of operating parameters on thermodynamic analysis of lignocellulosic biomass gasification.

3. Theoretical considerations

The most important equations used in exergy-based sustainability analyses of the biomass gasification process are tabulated in **Table 4**. In analyses, the exergetic contents of all the streams involved in the process should first be determined using the tabulated equations. Then, some dimensional/dimensionless exergetic indices should be calculated for the main components of the process and the overall system for comparison purposes.

4. Literature review

The gasification process converts organic compounds of biomass into a mixture of gases (mainly CO, H_2, CO_2, CH_4, and light hydrocarbons) in the presence of a gasifying agent at high temperatures (Situmorang et al., 2020). The gasification process mainly consists of four steps: drying, devolatilization, partial oxidation, and reduction. These involve numerous endothermic and exothermic reactions (water-gas shift, methanization, steam reforming, etc.) occurring simultaneously (La Villetta et al., 2017). The drying stage typically reduces the biomass moisture content to below 15% at temperatures lower than 200°C, while the devolatilization step (350–600°C) decomposes the organic material (such as hemicellulose, cellulose, and lignin) into volatile compounds and solid residues. In the oxidation zone, the volatiles and char are oxidized to CO, CO_2, and H_2O *via* exothermic reactions at high temperatures, while the devolatilization products are transformed to CO, CH_4, and H_2 in the reduction stage (Gao et al., 2020; Situmorang et al., 2020). In general, several factors, including biomass composition, operating conditions, and reactor type/configuration, affect the exergy efficiency of the exothermic biomass gasification process (Abuadala and Dincer, 2012). **Figure 5** illustrates a principal component analysis of the most effective parameters on the exergy efficiency of biomass gasification. The carbon, nitrogen, and ash content of biomass significantly contribute to the first principal component, while the volatile



Cluster 1: Integrating solid oxide fuel cell/organic Rankine cycle with biomass gasification systems and using exergy analysis and its extensions for their analysis (N=101).
Cluster 2: Thermodynamic analysis of biomass gasification systems consolidated with combined heat and power and combined cooling heating and power plants (N=36).
Cluster 3: Sustainability aspects analysis of hydrogen production from biomass gasification (N=105).
Cluster 4: Effect of operating parameters on thermodynamic analysis of lignocellulosic biomass gasification (N=133).

Fig. 4. Bibliographic coupling clustering indicating the most important research themes in exergy sustainability analysis of biomass gasification systems (N is the number of articles in each cluster).

Table 4.
Most important equations used in exergy analysis of biomass gasification processes.*

Equation	**Application**	**Item(s) in the equation**		
		Notation(s)	**Unit**	**Description**
General formulas:				
$\sum_i \dot{m}_i = \sum_e \dot{m}_e$	Mass balance of a component	$\dot{m}$	kg/s	Mass flow rate
$\sum_i \dot{Q}_i + \sum_i \dot{m}_i\, h_i = \dot{W} + \sum_e \dot{m}_e\, h_e$	Energy balance of a component	$\dot{Q}$ $\dot{W}$ h	kW kW kJ/kg	Heat rate Work rate Specific enthalpy
$\sum_i \dot{Q}_i \left(1 - \frac{T_0}{T_i}\right) + \sum_i \dot{m}_i\, ex_i = \dot{W} + \sum_e \dot{m}_e\, ex_e + \dot{E}_d$	Exergy balance of a component	ex $\dot{E}$ T $\dot{E}_d$	kJ/kg kW K kW	Total specific exergy Exergy rate Temperature Exergy destruction rate
$ex = ex^{ph} + ex^{ch} + ex^{ke} + ex^{pe}$	Total specific exergy of a stream	ex^{ph} ex^{ch} ex^{ke} ex^{pe}	kJ/kg kJ/kg kJ/kg kJ/kg	Specific physical exergy Specific chemical exergy Specific kinetic exergy Specific potential exergy
Physical exergy:				
$ex^{ph} = h - h_0 - T_0 (s - s_0)$	Specific physical exergy of a pure stream	s	kJ/kg K	Specific entropy
$ex^{ph} = c\left(T - T_0 - T_0 ln\left(\frac{T}{T_0}\right)\right)$	Specific physical exergy of a mixed or even pure liquid stream	c	kJ/kg K	Specific heat capacity
$ex^{ph} = c\left(T - T_0 - T_0 ln\left(\frac{T}{T_0}\right)\right) + RT_0 ln\left(\frac{P}{P_0}\right)$	Specific physical exergy of a mixed or even pure gaseous stream	R P	kJ/kg K kPa	Gas constant Absolute pressure
$c = \sum_{j=1}^{n} x_j c_j$	Specific heat capacity of a mixed liquid/gaseous stream	x	(–)	Mass fraction
$R = \frac{\bar{R}}{\sum_{j=1}^{n} y_j M_j}$	Gas constant of a mixed liquid/gaseous stream	$\bar{R}$ y M	kJ/mol K (–) kg/mol	Universal gas constant (8.314) Mole fraction Molecular weight
$ex^{ph} = [c_a + \omega_a c_v](T_a - T_0) - T_0\{[c_a + \omega_a c_v] \ln\left(\frac{T_a}{T_0}\right) - [R_a + \omega_a R_v] \ln\left(\frac{P_a}{P_0}\right)\} + T_0\{[R_a + \omega_a R_v] \ln\left(\frac{1 + 1.6078\omega_a}{1 + 1.6078\omega_0}\right) + 1.6078\omega_0\, R_a \ln\left(\frac{\omega_a}{\omega_0}\right)\}$	Specific physical exergy of the air stream	C_a C_v R_a R_v T_a P_a ω_a ω_0	kJ/kg K kJ/kg K kJ/mol kJ/mol K kPa (–) (–)	Specific heat capacity of air Specific heat capacity of water Gas constants of air Gas constants of water vapor Absolute temperature of air Absolute pressure of air Humidity ratio of air Humidity ratio of reference state
Chemical exergy:				
$ex^{ch} = \sum_j \frac{1}{y_j M_j}\left(\sum_j y_j \varepsilon_j + \bar{R}T_0 \sum_j y_j \ln(y_j)\right)$	Specific chemical exergy of a gaseous stream	ε_j	kJ/mol	Standard chemical exergy of the jth stream
$\varepsilon = -\Delta G + \sum_{Product} n_m \varepsilon_m - \sum_{Reactant} n_l \varepsilon_l$	Standard chemical exergy of an inorganic compound	G n	kJ/mol (–)	Gibbs free energy Mole number
$ex^{ch} = 100 * \{363.439[C] + 1075.633[\mathrm{H}] - 86.308[\mathrm{O}] + 4.14[\mathrm{N}] + 190.798[\mathrm{S}] - 21.1[\mathrm{A}]\}$	Specific chemical exergy of both solid and liquid organic compounds	$[C]$ $[H]$ $[O]$ $[N]$ $[S]$ $[A]$	wt% wt% wt% wt% wt% wt%	Carbon content Hydrogen content Oxygen content Nitrogen content Sulfur content Ash content

Table 4.
continued.

Equation	**Application**	**Item(s) in the equation**		
		Notation(s)	**Unit**	**Description**
$ex^{ch} = \beta \times LHV$ For biomass: $\beta = \frac{1.044+0.016\left(\frac{[H]}{[C]}\right)-0.3493\left(\frac{[O]}{[C]}\right)\left[1+0.0531\left(\frac{H}{C}\right)\right]+0.0493\left(\frac{N}{C}\right)}{1-0.4124\left(\frac{O}{C}\right)}$ For bio-oil: $\beta = 1.0374 + 0.0159\left(\frac{[H]}{[C]}\right) + 0.0567\left(\frac{[O]}{[C]}\right)$ For Biochar: $\beta = 1.0437 + 0.1869\left(\frac{[H]}{[C]}\right) + 0.0617\left(\frac{[O]}{[C]}\right) + 0.0428\left(\frac{[N]}{[C]}\right)$	Specific chemical exergy of biofuel	LHV	kJ/kg	Lower heating value of fuel
Kinetic exergy:				
$ex^{ke} = \frac{1}{2 * 1000}V^2$	Specific kinetic exergy of a stream	V	m/s	Velocity
Potential exergy:				
$ex^{pe} = \frac{1}{1000}gz$	Specific potential exergy of a stream	g z	m^2/s m	Gravitational acceleration constant Height
Exergetic indicators:				
$\phi = \frac{\dot{E}_e}{\dot{E}_i} = 1-\frac{\dot{E}_d}{\dot{E}_i}$	Universal exergy efficiency of a biofuel production system	ϕ	%	Universal exergy efficiency
$\psi = \frac{\dot{E}_{useful\ product(s)}}{\dot{E}_i}$	Functional exergy efficiency of a biofuel production system	ψ	%	Functional exergy efficiency
$I\dot{P} = (1-\phi)(\dot{E}_i-\dot{E}_e)$	Exergetic improvement potential rate of a process	$I\dot{P}$	kW	Exergetic improvement potential rate
$DP = \frac{\dot{E}_d}{\dot{E}_i} = 1-\phi$	Depletion number of a component/system	DP	(–)	Depletion number
$SI = \frac{1}{DP}$	Exergetic sustainability index of a process	SI	(–)	Sustainability index
Subscripts: *i*: inlet stream, *e*: exit stream, *d*: destruction, 0: reference state, *j*, *m*, *l*: numerators, *tot*: total.				

* Adapted from Soltanian et al. (2020 and 2022); Torres et al. (2020).

matter and fixed carbon of biomass mainly contribute to the second principal component (**Fig. 5a**). As shown in **Figure 5b**, the first principal component is mainly attributed to temperature and gasifying agent/biomass ratio, while pressure significantly contributes to the second principal component. The exergy efficiency is positively correlated with the carbon and hydrogen contents of biomass (**Fig. 5a**). The oxygen, nitrogen, and ash contents of biomass are negatively correlated with the exergy efficiency of the gasification process because of their negative effects on biomass chemical exergy. The exergy efficiency of the process is strongly correlated with temperature, showing the importance of this operating parameter in exergy analysis (**Fig. 5b**).

Operating temperature is one of the most significant parameters in biomass gasification because of its direct effect on the devolatilization reactions as well as the process efficiency and syngas yield. Higher temperatures could marginally promote gasification reactions (i.e., water gas shift reaction, methane reforming, Boudouard, and cracking reactions), thus resulting in lower tar and char formation (Shahbaz et al., 2020). Note that the gasification process is commonly conducted at atmospheric pressure in order to discount capital and operating costs. However, pressurized regimes could enhance the gasification efficiency by suppressing tar formation and achieving easier recarbonization of CO_2 (Ramos et al., 2018). The other important operating parameter is gasifying agent/biomass ratio which significantly affects the resultant syngas composition and its calorific value (La Villetta et al., 2017).

Figure 6 depicts a contour diagram indicating the relationship between the main operating conditions of biomass gasification (i.e., operating temperature, pressure, and gasifying agent/biomass) and exergy efficiency. Higher exergy efficiency values are obtained at temperatures, pressures, and gasifying agent/biomass ratios in the range of 850–1000 °C, 3.3–5.6 atm, and 1.5–2, respectively. Generally, increasing gasification temperature promotes the water gas shift and steam reforming reactions, leading to higher H_2 and CO concentrations while raising the process exergy efficiency. In addition, exothermic reactions such as CO_2 and CH_4 forming reactions are suppressed by increasing the gasification temperature owing to the promotion of Boudouard and methane reforming reactions, respectively (Echegaray et al., 2019). Like reaction temperature, the gasifying agent/biomass ratio markedly affects syngas composition and calorific value. Lower gasifying agent/biomass ratios enhance solid char and methane forming reactions, lowering the exergy efficiency of the process. Note that a higher gasifying agent/biomass ratio can provide a sufficient amount of oxidizing agents to complete primary and secondary decomposition reactions. Therefore, increasing the gasifying agent/biomass

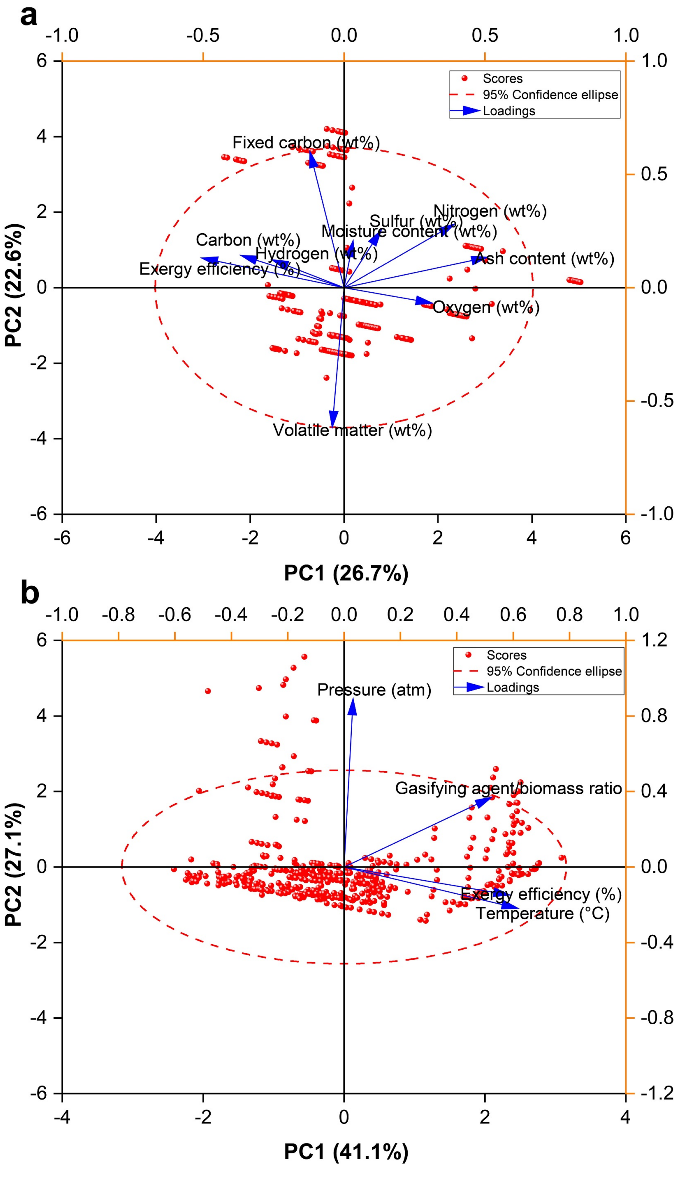


Fig. 5. Bibliographic Principal component analysis indicating the effects of biomass compositions **(a)** and operating conditions **(b)** on the exergy efficiency of the gasification process. The dashed oval identified the confidence level of the collected data.
Data collected from Abuadala et al. (2010); Abuadala and Dincer (2010); Beno Wincy et al. (2020); Bhattacharya et al. (2011); Cohce et al. (2011); Colpan et al. (2010); Couto et al. (2017); Cruz et al. (2017); Echegaray et al. (2019); Fryda et al. (2008); Gu et al. (2019); Heyne et al. (2013); Hosseinpour et al. (2020); Jia et al. (2015); Juraščík et al. (2010); Kalinci et al. (2010); Kartal and Özveren (2021); Khoshgoftar Manesh and Jadidi (2020); Loha et al., 2011; Mahapatro et al., 2020; Manatura et al., 2017; Michailos et al., 2017; Mojaver et al., 2019; Nakyai et al., 2020; Parvez and Khan (2020); Patel et al. (2017); Prins et al. (2005); Ptasinski et al. (2007); Puadian et al. (2014); Reyes et al. (2021); Rupesh et al. (2020); Song et al. (2013); Sues et al. (2010); Tang et al. (2016); Thamavithya et al. (2012); van der Heijden and Ptasinski (2012); Vitasari et al. (2011); Wu et al. (2014 and 2020); Yan et al. (2006); Zhang et al. (2012); Zhao et al. (2021); Zhong et al. (2021).

ratio can improve the exergy efficiency of the biomass gasification process (Samimi et al., 2020).

Biomass composition plays a key role in the exergy analysis of biomass gasification by affecting the quantity and quality of the products. A contour diagram indicating the correlation between biomass composition (both ultimate and proximate) and exergy efficiency of biomass gasification is illustrated in **Figure 7**. Higher exergy efficiency values are obtained at carbon, hydrogen, and oxygen contents in the range of 45–55 wt%, 5.5–6.5 wt%, and 30–40 wt%, respectively. Carbon- and hydrogen-rich biomass feedstocks generally result in higher process exergy efficiency values by increasing the CO and H_2 concentrations in the syngas and elevating its calorific value. Higher exergy efficiency values are observed for nitrogen contents in the range of 0.2–2 wt%. It is noted that the amount of nitrogen should be minimized to avoid NH_3 and HCN formation, reduce NOx emissions, prevent catalysis deactivation, and facilitate syngas cleaning and conditioning (Watson et al., 2018). Higher exergy efficiency values are obtained for volatile matter, moisture content, and ash content ranges of 60–70 wt%, 8–12 wt%, and 2–6 wt%, respectively. Generally, ash-rich biomass feedstocks result in a syngas having less exergy since the main gasification reactions such as water-gas shift, methanation, and steam reforming are suppressed at higher ash contents. Increasing the volatile matter of biomass can increase the concentration of organic vapors such as paraffinic and aromatic hydrocarbons in the syngas, resulting in an increased process exergy efficiency (Díaz González and Pacheco Sandoval, 2020). Note that higher moisture contents complicate the combustion stage in the biomass gasification process, leading to a syngas with less energy and, consequently, a reduced exergy efficiency. In addition, wet biomass lowers the oxidation temperature of gasification, resulting in incomplete decomposition of the hydrocarbons formed during the devolatilization stage (La Villetta et al., 2017).

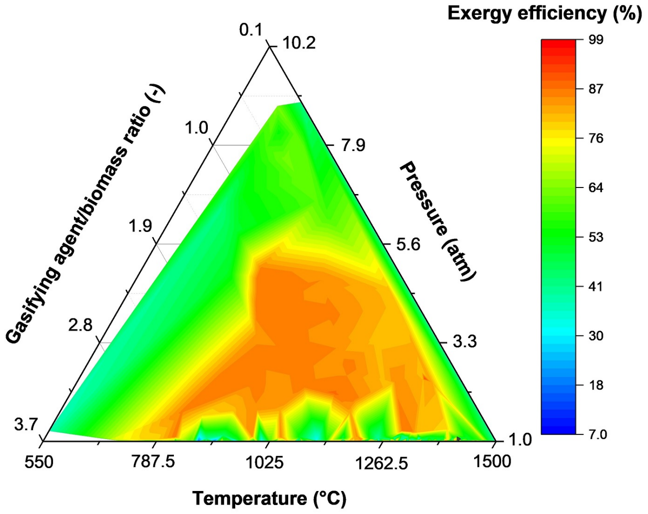


Fig. 6. Effect of operating parameters on the exergy efficiency of the biomass gasification process.
Data obtained from Abuadala et al. (2010); Abuadala and Dincer (2010); Beno Wincy et al. (2020); Fryda et al. (2008); Gu et al. (2019); Kartal and Özveren (2021); Loha et al. (2011); Manatura et al. (2017); Mojaver et al. (2019); Ptasinski et al. (2007); Rupesh et al. (2020); Song et al. (2013); Tang et al. (2016); Thamavithya et al. (2012); Vitasari et al. (2011); Wu et al. (2014); Zhao et al. (2021); Zhong et al. (2021).

The type of gasifying agent significantly affects biomass reactivity and syngas composition, thus impacting the exergy efficiency of the process. In order to achieve the desired syngas quality in downstream applications, oxygen, air, steam, CO_2, or their mixtures can be applied in the gasification process. **Table 5** summarizes the merits and limitations of the gasifying agents typically used in biomass gasification. **Figure 8** shows the exergy efficiency derived from different gasifying agents and its kernel density distribution curve. Obviously, a mixture of CO_2 and steam as a gasifying agent result in higher exergy efficiency values. This finding can be attributed to the role of steam in promoting the water-gas shift, steam reforming, and carbon oxidation reactions (Watson et al., 2018). In addition, CO_2 can promote the Boudouard and reforming reactions, thereby enhancing the exergy efficiency.

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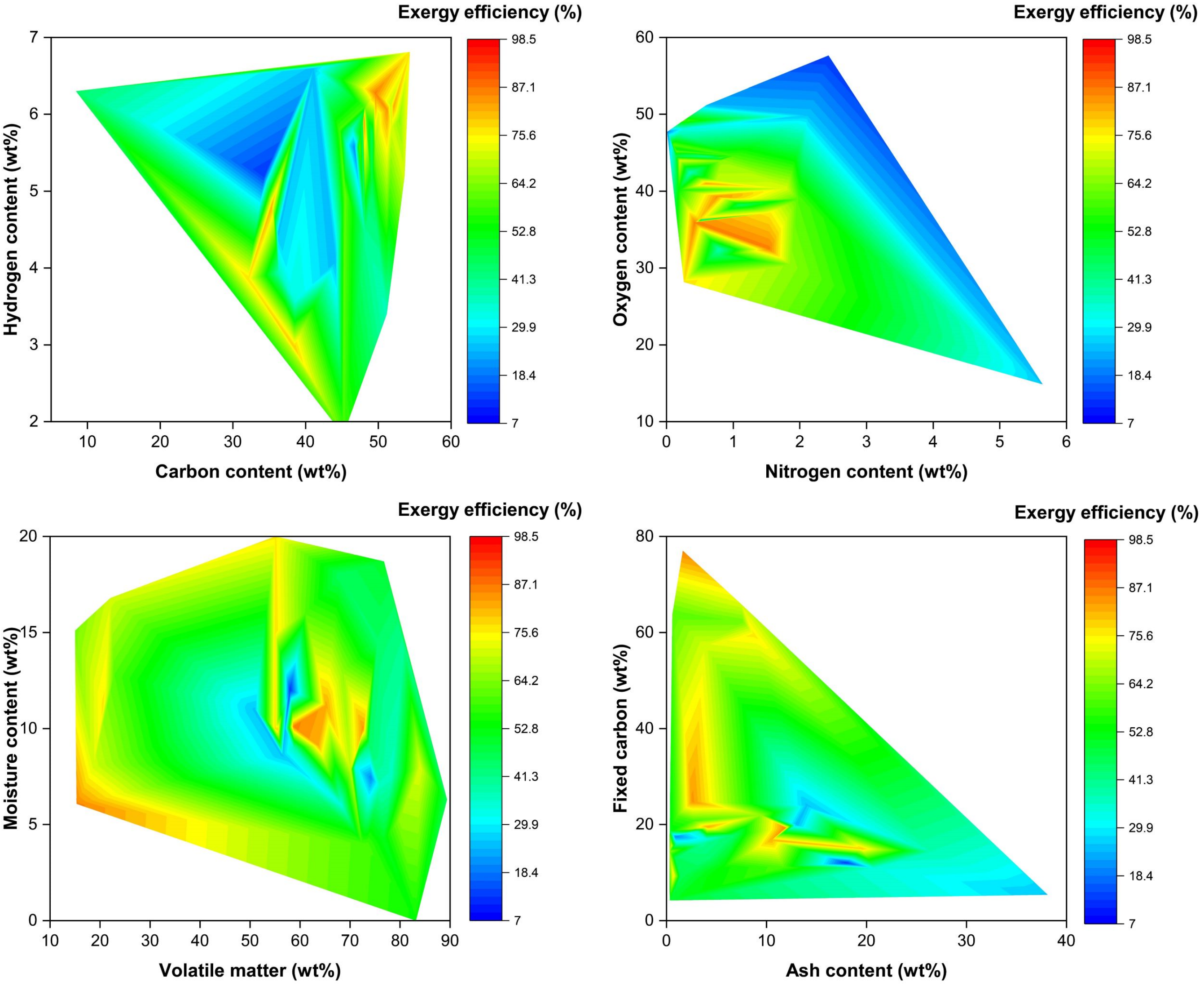


Fig. 7. Effect of biomass composition (both elemental and proximate) on the exergy efficiency of the gasification process.
Data obtained from Abuadala et al. (2010); Abuadala and Dincer (2010); Caglar et al. (2021); Echegaray et al. (2019); Fryda et al. (2008); Gu et al. (2019); Kalinci et al. (2010); Kartal and Özveren (2021); Khoshgoftar Manesh and Jadidi (2020); Loha et al. (2011); Mahapatro et al. (2020); Michailos et al. (2017); Prins et al. (2005); Reyes et al. (2021); Rupesh et al. (2020); Song et al. (2013); Tang et al. (2016); Wu et al. (2014).

Reactor type plays a major role in the quantity and quality of syngas during biomass gasification, thereby significantly affecting the exergetic features of the process. Typically, biomass gasification reactors are classified into fixed-bed (downdraft and updraft), fluidized-bed (bubbling and circulating), entrained flow, rotary kiln, and plasma reactors (Ren et al., 2019). In updraft gasifiers (counter-current), the biomass is fed from the top, the gasifying agent is injected from the bottom, and the produced gas flows out from the top side of the reactor. In downdraft gasifiers (co-current), the biomass feeding strategy is as in the updraft case, the gasifying agent enters at the sides, and the syngas exits from the bottom side of the gasifier. Fixed bed reactors have been widely used for biomass gasification due to their advantages, such as high thermal efficiency, high carbon conversion, and the capacity to handle wet biomass. However, they suffer from high tar content, low feedstock flexibility, and low syngas yield (Ren et al., 2020).

Fluidized bed gasifiers require high flow rates to fluidize biomass particles, resulting in enhanced mixing capability, uniformity in temperature distribution in the reactor, and good reaction and heat transfer rates. In addition, entrained flow gasifiers operate at higher temperatures and pressures (20–70 bar) and require fine particles to produce high surface contact; such gasifiers are usually employed for residues and waste gasification (Sikarwar et al., 2016). Plasma gasifiers ionize syngas molecules using electric discharge to improve tar degradation and syngas quality in the absence of an oxidizing agent. These reactors are suitable for decomposing toxic organic wastes into elemental molecules due to their high operating temperatures (Heidenreich and Foscolo, 2015). Plasma gasifiers are more complex due to their high operating temperatures and related energy requirements. **Table 6** summarizes the merits and limitations of various gasifier types. As depicted in **Figure 9**, the downdraft fixed-bed gasifier has the highest exergy efficiency among biomass gasification systems. This observation can be attributed to the excellent contact between the biomass and gasifying medium in the combustion stage, leading to the formation of high-quality syngas with low tar content (Wan et al., 2013; Ren et al., 2019). Circulating fluidized-bed and tubular gasifiers have relatively high exergy efficiencies because of their better heat and mass transfer features.

Table 5.
Advantages and disadvantages of selected gasifying agents.*

Gasifying agent	Advantages	Disadvantages
Air	Simple operation Mature technology Simple heating process Moderate char and tar content Low soot production	Lower CO and H_2 concentrations Lower efficiency and calorific value of syngas Higher contents of nitrogenous compounds in syngas Higher gas cleaning and separation costs
O_2	Relatively mature technology Negligible tar and char formation High-quality syngas production by enhancing H_2 and CO Small nitrogen dilution Lower reaction temperature	Higher capital and operating costs Higher process complexity Potential dangers associated with its container
CO_2	Higher energetic content of syngas Negative CO_2 emissions Higher gasification efficiency	Higher char production Longer reaction
Steam	Better carbon conversion feature Higher calorific value of syngas Higher concentrations of H_2 and CO in syngas Higher efficiency	Higher energy consumption Potential of higher tar formation

* Source: Abdoulmoumine et al. (2015); Agu et al. (2019); Ahmad et al. (2016); Díaz González and Pacheco Sandoval (2020); Habibollahzade et al. (2021); Hanchate et al. (2021); Molino et al. (2018); Qin et al. (2012); Ren et al. (2019); Sansaniwal et al. (2017); Tinaut et al. (2008).

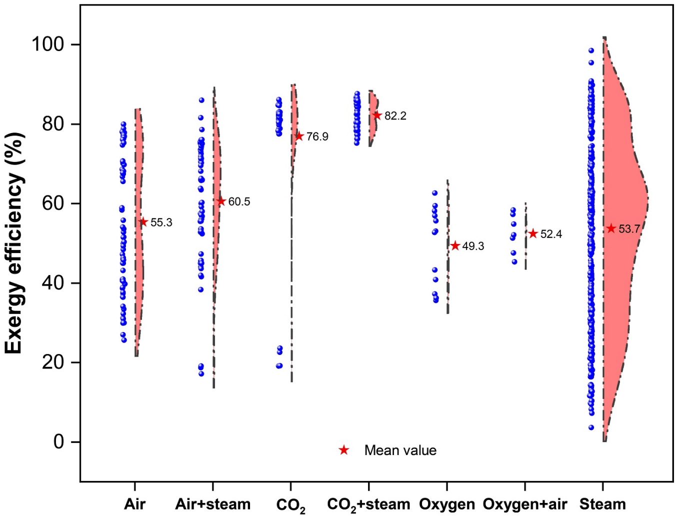


Fig. 8. Effect of gasifying agent on the exergy efficiency of biomass gasification.
Data obtained from Abuadala et al. (2010); Abuadala and Dincer (2010); Beno Wincy et al. (2020); Bhattacharya et al. (2011); Cohce et al. (2011); Colpan et al. (2010); Couto et al. (2017); Cruz et al. (2017); Echegaray et al. (2019); Fryda et al. (2008); Gu et al. (2019); Heyne et al. (2013); Hosseinpour et al. (2020); Jia et al. (2015); Juraščík et al. (2010); Kalinci et al. (2010); Kartal and Özveren (2021); Khoshgoftar Manesh and Jadidi (2020); Loha et al. (2011); Mahapatro et al. (2020); Manatura et al. (2017); Michailos et al. (2017); Mojaver et al. (2019); Nakyai et al. (2020); Parvez and Khan (2020); Patel et al. (2017); Prins et al. (2005); Ptasinski et al. (2007); Puadian et al. (2014); Reyes et al. (2021); Rupesh et al. (2020); Song et al. (2013); Sues et al. (2010); Tang et al. (2016); Thamavithya et al. (2012); van der Heijden and Ptasinski (2012); Vitasari et al. (2011); Wu et al. (2014 and 2020); Yan et al. (2006); Zhang et al. (2012); Zhao et al. (2021); Zhong et al. (2021).

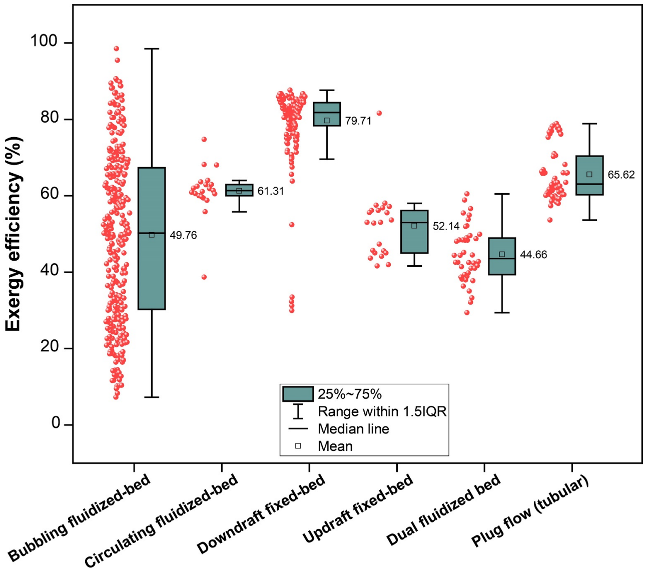


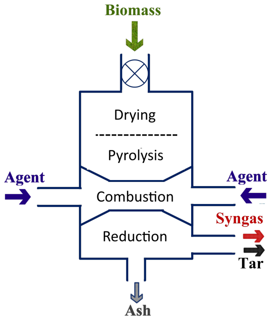
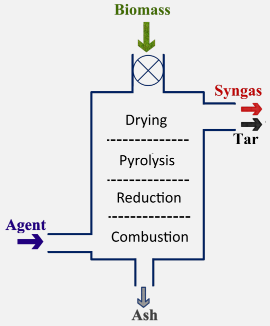
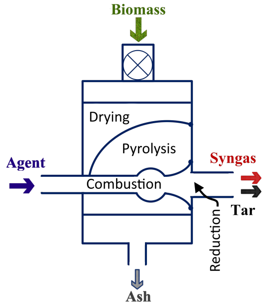
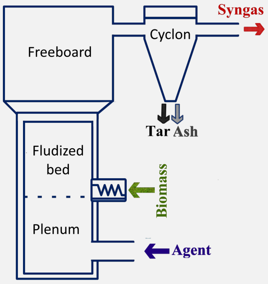
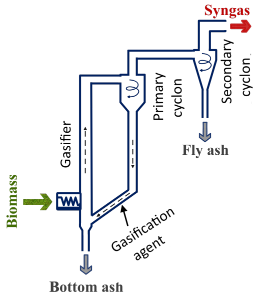
Fig. 9. Effect of reactor type on the exergy efficiency of biomass gasification.
Data obtained from Abuadala et al. (2010); Abuadala and Dincer (2010); Beno Wincy et al. (2020); Caglar et al. (2021); Couto et al. (2017); Echegaray et al. (2019); Hosseinpour et al. (2020); Jia et al. (2015); Juraščík et al. (2010); Kartal and Özveren (2021); Loha et al. (2011); Mahapatro et al. (2020); Manatura et al. (2017); Mojaver et al. (2019); Nakyai et al. (2020); Patel et al. (2017); Prins et al. (2005); Puadian et al. (2014); Reyes et al. (2021); Rupesh et al. (2020); Song et al. (2013); Sues et al. (2010); Tang et al. (2016); Thamavithya et al. (2012); Vitasari et al. (2011); Wu et al. (2014); Zhao et al. (2021).

5. Challenges and future directions

Biomass gasification involves high-temperature biomass processing, with a large amount of thermal energy exchanged between the reactor and the surroundings. Accordingly, thermodynamic measures like exergy analysis can effectively assess the efficiency, viability, and sustainability of such high-energy exchange processes. Exergy methods can weigh different energy and material flows by determining their potentials to create work, thereby providing a sound decision-making basis for engineers and designers concerning biomass gasification processes. Despite the unique features of this sustainability assessment tool, it suffers from some inherent drawbacks like the high sensitivity of results to reference environment conditions (temperature, pressure, and chemical composition). More specifically, the choice of datum level significantly affects the rate of exergy destruction and exergy loss, thus impacting the dimensionless exergetic indicators. In addition, exergy analysis can only determine information about the internal irreversibility of biomass gasification systems while it alone is incapable of providing insights concerning economic and environmental aspects. Accordingly, advanced exergy-based analyses (e.g., exergoeconomic and exergoenvironmental) need to be applied in future research as complementary tools for investigating, evaluating, and optimizing biomass gasification. In addition, exergoeconoenvironmental methods that analyze energy systems from thermodynamic, economic, and environmental perspectives simultaneously can be used for investigating sustainability aspects of biomass gasification (Aghbashlo and Rosen, 2018a). The exergy concept does not account for non-physical energy flows like labor. This issue can be effectively resolved using the extended exergy method proposed by Sciubba (2019), in which all physical and non-physical streams are translated to an exergy basis (Joule).

Various dimensionless exergetic indicators have been defined in the literature, and these are useful, especially for comparison purposes. However, there is no universal agreement among researchers regarding the

Table 6.
Comparison of biomass gasification systems.*

Reactor type	Operating temperature range	Advantages	Disadvantages	Schematic diagram
Downdraft fixed-bed	700–1200 °C	- Applicable for various kinds of biomass feedstock - High thermal efficiency and carbon conversion - Favored when a clean syngas gas with a low content of tar and particulates is desired - Favorable in small-scale power generation plant	- Only dense feedstock is applicable - Ash accumulation problem - High temperature in the exhaust gas - Difficulties in handling feedstock with high moisture and ash contents - Non-uniform temperature distribution - Difficulties in operation - High content of tar in syngas - Catalyst poisoning and deactivation - Low syngas yield and heating value	
Updraft fixed-bed	700–900 °C	- Applicable for various kinds of biomass feedstock - High thermal efficiency and carbon conversion - Low pressure drops - Low slag formation - Low dust content at higher temperatures - Simple and economic process - Handling biomass with different particle sizes	- Low syngas yield and heating value - Long engine start-up time - High tar and moisture in syngas - Difficulties in operation - Non-uniform temperature distribution - Needing gas cleanup for downstream application - Catalyst poisoning and deactivation - Increasing the probability of channeling and bridging phenomena	
Cross draft fixed-bed	Up to 1300 °C	- Applicable for various kinds of biomass feedstock - High thermal efficiency and carbon conversion - Simple configuration - High throughput and flexibility of syngas production - Low start-up time	- Low overall energy efficiency - High tar content in syngas - Poor reduction of CO2 concentration - Non-uniform temperature distribution - Difficulties in operation - Catalyst poisoning and deactivation - Low syngas yield and heating value - Not suitable for large-scale	
Bubbling fluidized-bed	800–900 °C	- High heat and mass transfer coefficients - Uniformity in temperature distribution - Simple ash removal system - Improved rate of reaction - Low reaction time - Economically feasible	- Operational complexity - Eutectic formation at higher operating temperatures - Needing high velocity of gas flow - High particulate and tar contents in syngas - Increasing the possibility of coalescence phenomena - Rapid char agglomeration	
Circulating fluidized-bed	900–1200 °C	- High heat and mass transfer coefficients - Uniformity in temperature distribution - Recycling of particulate matter - Possibility to employ a low-cost bed material - High throughput - Capability to operate at higher pressures (suitable for gas turbine operating)	- Complex process control - Needing for high velocity of the gasifying medium - High capital and operating costs - High particulate and tar contents in syngas - Bed particles agglomeration because of Si, K, and Ca in biomass	

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* Source: de Lasa et al. (2011); Janajreh et al. (2013); Mishra and Upadhyay (2021); Motta et al. (2018); Ren et al. (2019); Sikarwar et al. (2017); Watson et al. (2018).

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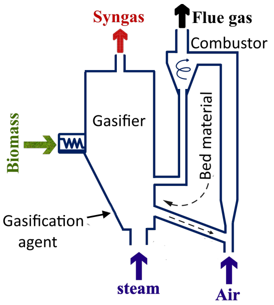
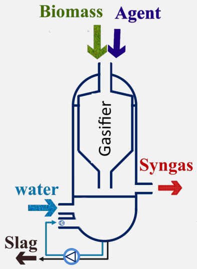
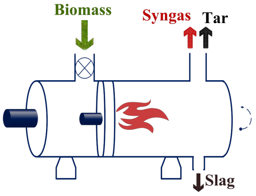
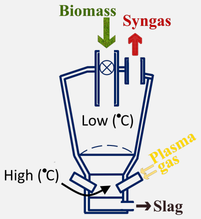
Table 6.
continued.

Reactor type	Operating temperature range	Advantages	Disadvantages	Schematic diagram
Dual fluidized-bed	850–1200 °C	- High solid transport rates - Uniformity in temperature distribution - High energy conversion - Low tar formation - H_2-rich syngas production - Low reaction time	- Bed particles agglomeration because of Si, K and Ca in biomass - Complex process control - High investment and maintenance costs - High tar content in syngas - Dust dragging in syngas	
Entrained flow	1300–1500 °C	- Very low tar formation - Short reaction time - Economical for large-scale applications Simple operation - High flexibility in feedstock selection	- Low cold gas efficiency - Needing for the high volume of gasifying agent - High investment and maintenance costs - Need for heat recovery - Only applicable for fine particles	
Rotary kiln	> 900 °C	- Suitable for waste biomass - Economical for large-scale applications - Simplicity in construction	- Difficulties in operation - High maintenance cost - Low syngas quality	
Plasma	Up to 10000 °C	- High feedstock flexibility (hazardous and non-hazardous) - High-quality syngas production - Minimized reformation of persistent organic pollutants (because of steep thermal gradients and material quench) - High reaction rates - Small reactor size at high throughput - Highest heat transfer among all gasifier types	- Need for the high volume of oxidation agent - High investment and operation costs - Requiring frequent maintenance - Safety problem due to high-temperature operation - High complexity - Requirement for biomass with small particle size - High probability of ash agglomeration	

* Source: de Lasa et al. (2011); Janajreh et al. (2013); Mishra and Upadhyay (2021); Motta et al. (2018); Ren et al. (2019); Sikarwar et al. (2017); Watson et al. (2018).

definition of some dimensionless exergetic indicators. This issue might cause misinterpretations and misunderstandings of reported data and make comparisons of the results from different studies difficult. For example, two exergy efficiency definitions, i.e., universal and functional approaches, can be found in the literature. The universal exergy efficiency Indicates the degree of irreversibility and exergy loss in a thermodynamic system. This indicator cannot objectively and reliably measure the exergetic effectiveness of biomass gasification systems. However, the functional exergy efficiency, which evaluates the degree of productiveness and usefulness of a thermodynamic system, can be utilized accurately and meaningfully to compare biomass gasification systems. Overall, exergetic formulations for biomass gasification systems need to be harmonized and standardized in future research to make the results more interpretable and comparable. Furthermore, the contribution of chemical exergy to the total exergy of the streams involved in the biomass gasification process is significantly higher than physical exergy. Nevertheless, various theoretical, semi-theoretical, and empirical models with different accuracy and reliability levels have been used in the literature to calculate the chemical exergy content of biomass feedstocks and resultant products (particularly tar and char). This issue can negatively affect the accuracy and reliability of the obtained

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exergetic metrics. Developing robust models using machine learning and other advanced techniques can effectively address the challenge. In addition, the exergy content of byproducts of biomass gasification (i.e., biochar and tar), which are often ignored in the published papers, should be considered in future research.

Many studies have been published on exergy analyses of integrated biomass gasification systems, such as the combination of biomass gasification with solid oxide fuel cell/organic Rankine cycle/combined heat and power. However, less attention has been paid to exergetically evaluating the advanced biomass gasification systems used to produce liquid transportation biofuels via the catalytic Fischer-Tropsch process or mixed alcohols generation via catalytic fermentation. Another effective option to improve the exergetic performance of biomass gasification systems is to use renewable thermal energy and electricity sources like solar, wind, and geothermal energy. In addition, advanced heat integration methods like pinch analysis and self-heat recuperation technology can provide tools to enhance the exergy efficiency of biomass gasification by decreasing heating and cooling demands. Plasma gasification, pressurized gasification, and co-gasification of biomass with fossil fuels should also be exergetically evaluated in future investigations.

6. Concluding remarks

The present review numerically scrutinizes, systematically reviews, and critically discusses the effects of various parameters (i.e., operating conditions and biomass composition) on the exergy efficiencies and performance characteristics of biomass gasification systems. The main concluding remarks obtained from this review are as follows:

- Unlike carbon and hydrogen contents of biomass, the exergy efficiency is negatively correlated with oxygen, nitrogen, and ash contents.
- The moisture content of biomass can markedly affect the exergetic performance of the gasification process.
- Among operating parameters, the reaction temperature is the most influential parameter on the exergy efficiency of biomass gasification. Gasifying agent/biomass ratio and operating pressure can markedly affect syngas composition.
- A mixture of CO_2 and steam leads to the highest exergy efficiency among the investigated gasifying agents.
- The best reactor configuration for biomass gasification is the downdraft fixed-bed owing to it exhibiting the highest exergy efficiency value.

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