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REVIEW ARTICLE

Syngas for Internal Combustion Engines, Current State, and Future Prospects: A Systematic Review

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ABSTRACT – Biomass is a potential alternative energy source. This study offers a comprehensive analysis of biomass gasification as an energy source, particularly its application in diesel engines, gas engines, and gas turbines. No specific research has been identified that addresses syngas utilization as fuel for internal combustion engines. The paper employs the PRISMA methodology to select and analyze observations. The examination encompasses four subjects: biomass, reactor gasification, operational parameters, and syngas for internal combustion. The Van Krevelen diagram is employed to analyze the characteristics of biomass that produce high-energy syngas, efficiency, variable calorific value of syngas, and decreased power output. Feedstock, gasification reactors, and operational conditions significantly influence the generation of biomass gasification syngas. A downdraft reactor is appropriate for small- to medium-scale gasification. The utilization of biomass gasification technology and syngas as fuel for internal combustion engines is investigated. The hydrogen-to-carbon ratio (H/C), oxygen-to-carbon ratio (O/C), high temperature, low ash content, low equivalence ratio (ER), and the amount of air in the syngas all affect its calorific value. The advantages of utilizing syngas include reduced pollutants, decreased reliance on diesel fuel, and a reduction in diesel fuel use in internal combustion engines. The disadvantages of syngas include necessary engine modifications, decreased thermal efficiency, the calorific value of syngas, and decreased power generation.

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1. INTRODUCTION

Currently, energy availability is critical to economic development. According to the International Energy Agency (IEA), energy demand increased by 70% in 2020 compared to 2011. Demand for fossil energy is expected to reach 78% by the end of 2040, up from 13% in 2013, while demand for bioenergy is expected to be 13%. Coal fossil energy sources account for over 38% of global electricity generation [1]. The use of fossil energy (e.g., coal) negatively impacts CO_2, SO_2, and NOx emissions [2]. Reducing gas and pollutant emissions from power plants is a serious global challenge [3]. Meanwhile, worldwide energy demand growth in the electrical sector is expected to increase by around 1% by 2030, with new renewable energy increasing by over 50% [4]. Biomass is a newer renewable energy source crucial in shifting towards a sustainable, low-carbon energy system. Biomass has multiple key advantages, such as serving as a renewable energy source, mitigating carbon emissions, providing economic and employment prospects, and promoting energy source diversification. [5].

In the last five years, many studies have been conducted on using biomass as an energy source, either in dual-fuel syngas–diesel fuel [6] or as a replacement for gas engines [7]. Maya et al. [8] have examined the impact of gasification technology and the environmental benefits of municipal solid waste (MSW) gasification on power generation in Brazil. Gonzales et al. [9], Sansaniwal et al. [10], [11], and Indrawan et al. [12] have reviewed the utilization of biomass to generate electricity. Situmorang et al. [13] evaluated gasification systems for small-scale generators rated less than 200 kW and showed that biomass can be used as an energy source for electricity generation. Fiore et al. [14] have investigated the effect of using syngas in internal combustion engines, including as a dual fuel for internal combustion engines, engine fuel, and diesel fuel. Nanda and Berruti [15] have investigated the weaknesses and advantages of biomass conversion technology. Teoh et al. [16] have stated that hydrogen gas has a significant market share because of its high thermal efficiency, low fuel consumption, and low energy consumption. The usage of hydrogen minimizes pollutants such as smoke, hydrocarbons, CO_2, and NOx.

Despite the growing interest in syngas technology, there is a lack of comprehensive reviews focusing on biomass properties, gasification technology, and the use of syngas as a dual fuel for internal combustion engines. There are discrepancies in explanations of the biomass selection process, gasification reactor technology, syngas cleaning procedures, syngas–diesel dual fuel, and exhaust gas emissions from syngas use. In the most recent decade, numerous publications and studies have been published on the use of syngas as a dual fuel for diesel or internal combustion engines [14], [17], [18]. Syngas consists of CO, CH_4, and H_2 [19], [20] and has a calorific value similar to that of diesel [21]. To better understand the current use of syngas as a dual fuel, its issues, and future prospects, a thorough review of biomass as an energy source

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is required. This review paper identifies the type of biomass that produces syngas with the highest calorific value, the operating conditions that yield the highest syngas output, and the latest advancements in using syngas as a fuel for internal combustion engines. It also presents the engine performance and gas emissions for dual-fuel syngas–diesel and syngas–natural gas combustion.

2. METHODS AND MATERIALS

This review paper followed the preferred reporting items for systematic reviews and meta-analysis (PRISMA) guidelines. The PRISMA methodology has four stages [22]. The first stage is data collecting, which involves searching for credible peer-reviewed journal publications. The essential words were "dual-fuel, syngas–diesel, internal combustion engine, biomass for energy, waste energy for internal combustion engines, and emissions." Literature searches were limited to 2010–2022. Google Scholar and Science Direct are the two most commonly utilized databases for literature searches. Our search found 221 reputable papers.

The second stage of data screening is based on the abstract and title. Irrelevant papers are discarded from the data collection. The criteria for selecting papers were that the abstract includes information about the biomass used, the composition of the produced syngas, the gasification technique, and dual-fuel syngas–diesel for internal combustion. The biomass represented in the manuscript is commonly used in the gasification process, and its selection is not dependent on the maximum calorific value of the syngas. The makeup of this biomass greatly influences the properties of the syngas generated during the gasification procedure. Papers concerning biomass were included in the manuscript if they provided specific information regarding proximate and ultimate testing, gasification agents and temperature, and the type of reactor. From this screening stage, 156 relevant papers were identified, including 128 articles and 28 relevant review papers.

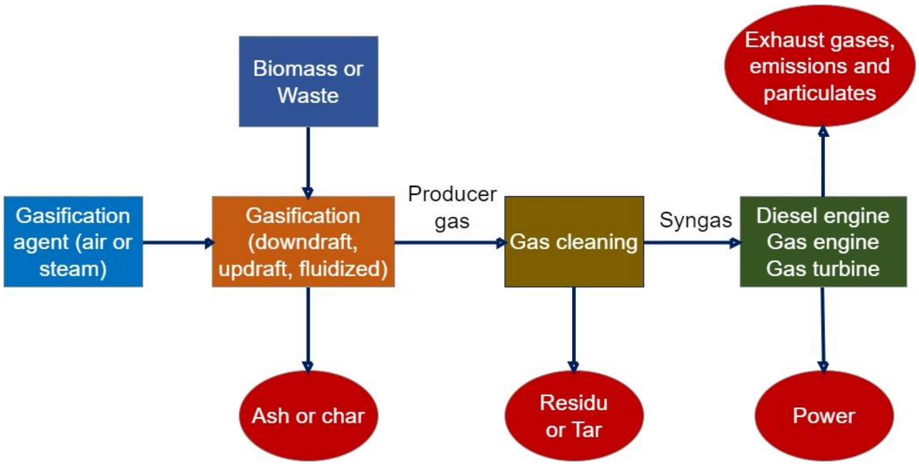

Figure 1. Schematic diagram of biomass or waste-to-energy gasification-based setup of a diesel engine, gas engine or gas turbine

Third stage: eligibility. The criteria for selecting papers include the presence of experimental data. The data collected include the proximate and ultimate testing results, the gasification technology employed, and the volume % composition of the produced syngas, including CO, CH_4, and H_2. The fourth stage of PRISMA involves data analysis through meta-analysis and descriptive analysis. Data processing and analysis employ a data summary strategy in the form of tables and graphics. The analysis was performed descriptively. Figure 1 illustrates the flow of discussion in this review study, which is a schematic diagram of biomass or waste-to-energy gasification-based setup of a diesel engine, gas engine or gas turbine

3. RESULT AND DISCUSSION

3.1 Feedstock Biomass

Syngas cleaning, gasification agent (air, oxygen, or steam), gasifier reactor, and biomass content are the factors that impact biomass gasification. Cellulose, hemicellulose, and lignin concentration determine biomass selection. The gasification process uses reactors with fixed beds, fluidized beds, and entrained flows. There are numerous chemical processes involved in gasifier reactor gasification. Filtration is necessary to remove impurities, such as sulfur, solid particles, and tar, from syngas before it can be used as fuel in an internal combustion engine. [24,25].

Biomass has emerged recently as the primary global energy source, replacing fossil fuels. Biomass can come from various sources, including forest waste, agricultural residues, municipal solid waste, plantation waste, and industrial forest plantations. The calorific value, carbon content, moisture, density, and other biomass parameters are determined by geographical conditions [10]. Ren et al. [23] and Molino et al. [24] have developed criteria to determine the influence of biomass characteristics that influence the results of biomass syngas gasification, specifically, biomass type, particle size, moisture content, and ash content, which are briefly summarised in Table 1.

The efficiency of the gasification process is directly affected by the particle size. The gasification reaction occurs more rapidly due to the increased contact surface area resulting from the small particle size, producing CO and H_2. Reactor design needs to be more targeted because of this vulnerability. A large particle size leads to a poor surface-to-volume ratio. Consequently, more tar products are produced, and the gasification efficiency is low, as shown in Table 1. Biomass particle size is an important factor in the gasification process that affects reaction rate, syngas quality, reactor design, and operating costs. Optimal particle size control is key to improving the efficiency and effectiveness of the gasification process [24,25].

Table 1. Characteristics of biomass in the gasification process

Feedstock parameters	Feedstock parameters, observations, results
Biomass type	• The major components in the gasification process are cellulose, hemicellulose, and lignin content. • The higher the cellulose and hemicellulose to lignin ratios, the higher the syngas results.
Moisture content	• The quality and energy efficiency are improved when the water content is lower. When the water content is between 30% and 40%, the tar content increases. • A water content between 10% and 20% is recommended for gasification. • The maximum water content for updraft reactors is 60%, and the maximum water content for downdraft reactors is 25%.
Particle size	• Reducing biomass particle size increases heat transfer area, gasification efficiency, and eventually hydrogen concentration and carbon conversion. • Particle size should be between 0.15 and 51 mm.
Ash content	• An ash content of 2% w/w biomass can be used as feedstock for updraft-type reactors. • Biomass with an ash content greater than 10% w/w can be used as feedstock for downdraft-type reactors. • Biomass with an ash level greater than 20% w/w may be difficult to gasify. • Biomass with an ash level greater than 10% w/w produces slag.

Source: Ren et al. [23] and Molino et al. [24]

Moisture refers to the water content of a solid fuel. The below formula [25] can be used to determine how moisture content affects the heating value of a fuel.

$$LHV_f = HHV_f - h_g\left(\frac{9H}{100} + \frac{MC}{100}\right) \tag{1}$$

where LHV_f is the lower heating value, HHV_f is the upper heating value, h_g is the latent heat of steam (2.26 MJ/kg), H is the hydrogen, and MC is the moisture content. According to Eq. (1), the calorific value of solid fuel decreases as its water content increases and vice versa. More heat is needed to evaporate moisture when the water content is higher. [26], [27]. Gasifier reactor design, syngas output quality, and energy conversion efficiency are all greatly affected by biomass moisture content. Converting carbon into syngas becomes less efficient when dealing with water-rich biomass because more energy is needed to remove this moisture. The consequence is that the energy originally allocated for the production of CO and H_2 gas is redirected towards the evaporation of the water present in the biomass. The ideal moisture content for the gasification process is 10% to 20% [29,30].

The sulfur and nitrogen content of biomass leads to pollutants, such as CO_2 and SO_2. The composition of lignin, cellulose, and extractive compounds significantly impacts the fixed carbon levels [28], [29], [30], [31], [32]. Volatile matter (VM) influences the combustion of materials. The quantity of volatiles in a material improves its ability to burn and ignite. In contrast, combustion is impacted by low-volatile substances [23]. Biomass fuels have a high calorific value because they release as much heat energy as possible per mass or volume of fuel when burned. The torrefaction process is a low-temperature carbonization method that can convert biomass into fuel with a calorific value comparable to coal. Carbonization is the process of biomass thermal degradation at temperatures between 300 and 800 °C, usually in an oxygen-free environment. Biomass moisture content will be significantly reduced during carbonization [29,33]. Carbon residue is produced as a by-product of this process, which involves the breakdown of the volatile components of the biomass. The calorific value of biomass can be increased by increasing its carbon concentration, leading to larger carbon- and oxygen-to-hydrogen ratios. [28], [29], [30], [31], [32]. The torrefaction process reduces the O/C and H/C ratios.

Table 2. Average ultimate and proximate analysis of biomass

Biomass	Ultimate analysis (% w/w)					Proximate analysis (%w/w)				HHV (MJ/kg)	Reference
	C	H	O	N	S	VM	FC	Ash	MS		
Corn	45.71	5.86	43.25	0.74	0.19	72.91	14.81	4.96	7.67	18.35	[33], [34], [35], [36], [37], [38], [39]
Rice husk	40.91	4.48	43.10	1.01	0.16	62.51	16.12	16.56	9.26	14.70	[36], [40], [41], [42], [43]
MSW	51.23	6.12	34.89	0.64	0.38	70.90	12.43	10.29	13.61	21.31	[32], [44], [45], [46], [47], [48], [49], [50]
Shell coconut	49.95	5.61	42.20	0.91	0.05	59.39	24.60	9.63	8.78	19.43	[51], [52], [53], [54]
Palm kernel oil	47.44	5.97	43.33	1.39	0.33	80.08	11.26	5.64	8.75	18.94	[55], [56], [57], [58], [59], [60]
Sawdust	48.94	6.33	42.57	0.47	0.36	77.45	17.16	1.17	8.17	20.15	[61], [62], [63], [64], [65], [66], [67], [68], [69]
Woodchips	49.58	5.87	43.66	0.59	0.08	79.06	16.19	1.33	8.42	19.68	[70], [71], [72], [73], [74], [75], [76], [77], [78]
Wood pellets	49.30	5.93	39.85	1.09	0.22	78.06	17.17	1.95	8.17	20.05	[32], [76], [79], [80], [81], [82], [83], [84], [85], [86]
Wood chars	71.10	4.42	21.98	0.38	0.01	40.34	56.13	3.32	5.23	27.68	[28], [29], [30], [31]

Table 2 lists nine forms of biomass utilized as energy sources. Figure 2 presents the average O/C and H/C for nine biomasses as represented on the van Krevelen diagram. O/C is the ratio of one mole of oxygen to one mole of carbon, whereas H/C is the ratio of one mole of hydrogen to one mole of carbon. Biomass heated or preheated to 300 °C will have characteristics comparable to coal. The image shows that when the O/C ratio increases, the heating value (HHV)- decreases. According to the graph, the MSW and wood pellets have the lowest O/C ratio, whereas corn and woodchips have the greatest. The biggest impact was on the HHV of MSW, while the lowest was on woodchips (Table 2).

Buragohain et al. [87] have developed a relation that explains how different ratios of oxygen to carbon and hydrogen to carbon affect syngas output and the lower heating value (LHV):

$$LHV_g = 2.588T^{0.114}(H/C)^{-15.281}(O/C)^{14.451}(O/H)^{-16.497} \tag{2}$$

$$Y_{syngas} = 0.678T^{-0.104}(H/C)^{16.498}(O/C)^{-16.933}(O/H)^{17.798} \tag{3}$$

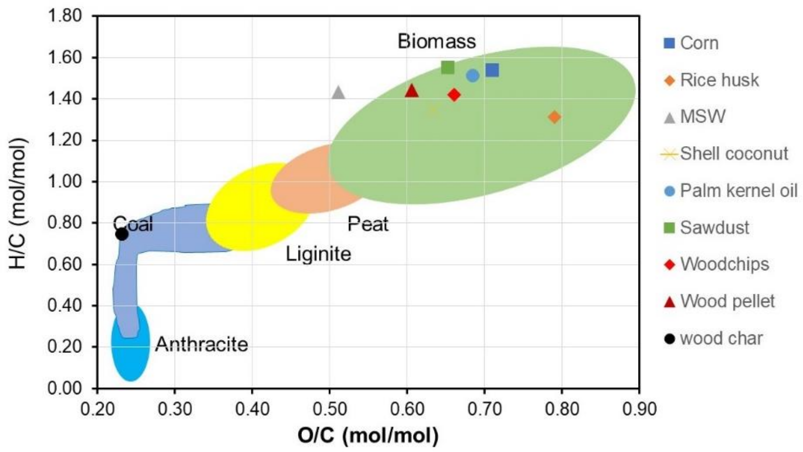

Figure 2. Biomass van Krevelen diagram

A lower O/C ratio and an increase in the H/C and O/H ratios increase syngas yield and decrease LHV, as shown by Eqs. (2) and (3). High-hydration-to-low-temperature biomass materials include MSW, sawdust, and palm kernel oil. The high-O/H biomass category includes materials such as rice husks, coconut shells, and woodchips. The H/C and O/C ratios of biomass should be considered when selecting it as a fuel feedstock. The results of this research are relevant to research from Zhang et al. [88]. In addition to the O/C and H/C ratios, quality biomass will result in high syngas composition, yield, and LHV. Fixed carbon (FC), VM, hydrogen (H), oxygen (O), ash content (Ash), and water content (MS) all have an impact on the syngas composition, yield, and low LHV. This is explained by the relations given by Nimmanterdwon et al. [89] and Sreejith et al. [90]:

$$Y_{\text{syngas}} = 216.18\,FC + 216.16\,VM - 3.68\,Ash - 178.41\,C + 621.76\,H - 377.19\,N - 242.85\,O \tag{4}$$

$$\mathrm{LHV_g} = 16.003 - 0.134\ \mathrm{C} + 4.167\ \mathrm{H} - 0.298\ \mathrm{O} - 0.067\ \mathrm{MS} + 0.156\ \mathrm{CCE} + 0.02791\mathrm{T} - 4.4701\ \mathrm{S/B} \tag{5}$$

According to Eq. (4), the higher the FC, VM, and H, the greater the syngas yield. VM is the part of biomass that easily evaporates at high temperatures. In addition to other organic compounds, VM is involved in the formation of compounds containing hydrogen and CO. An important factor in the final syngas quality is the material content and quantity of volatiles. During gasification, FC is used as a carbon source. During gasification, the FC reacts with the gasification agents and volatile chemicals to form syngas. For gasification to occur, both volatile molecules and FC must be present. Gasification uses FC as a carbon source, which creates gases such as CH_4, CO_2, and CO, while volatile chemicals contribute to the formation of syngas.

Similarly, a high concentration of C and O reduces syngas output. However, according to Eq. (5), if the C and O concentrations are high, the LHV of the gas will drop, whereas if C and O are low and H is high, the LHV and syngas yield would increase. In Table 2, the biomasses with the highest H concentrations are MSW and sawdust. Palm kernel oil, sawdust, woodchips, and wood pellets are examples of biomass that contain more than 90% VM and FC. VM and FC will influence the composition of syngas produced by gasification [40]. Ash content and biomass type affect gasification efficiency and syngas production. High ash levels can block gas flow, reduce process efficiency, and corrode the reactor. Syngas quality can suffer from ashing. Biomass gasification outcomes are sensitive to lignin, cellulose, and hemicellulose concentration. Increasing the ratios of cellulose and hemicellulose to lignin improves biomass gasification syngas quality. Optimizing biomass with low ash and high H/C and O/C ratios improves process efficiency and syngas quality.

Palm kernel oil and wood pellets are two of the four biomasses with low carbon and oxygen concentrations but high H_2 concentrations. Syngas hydrogen production is proportional to biomass hydrogen content. The calorific value grows with the hydrogen-to-carbon ratio. The composition of the produced gases, especially H_2 and CO, affects LHV. Carbon monoxide is colder than H_2. As the H_2 fraction increases, the syngas calorific value increases. A higher biomass hydrogen content will increase syngas LHV. Because CO and CO_2 provide less energy than H_2, biomass with a higher carbon content and lower hydrogen content will create syngas with a lower LHV [35,42]. As a result, this biomass can be considered a gasification feedstock when using syngas–diesel or syngas–natural gas.

The yield of syngas is determined by the gas composition of CO, CH_4, and H_2 (% vol). To understand how carbon, hydrogen, and oxygen affect syngas yields of CO (%vol), CH_4 (%), and H_2 (%vol), Pradhan et al. [91] have developed a linear regression correlation. The following equations represent this relationship:

$$\mathrm{CO} = -35.141 + 0.845\ \mathrm{C} - 0.852\ \mathrm{H} + 0.514\ \mathrm{O} + 0.304\ \mathrm{N} \tag{6}$$

$$\mathrm{CH_4} = -0.579 + 0.006\ \mathrm{C} + 0.027\ \mathrm{H} + 0.007\ \mathrm{O} \tag{7}$$

$$\mathrm{H_2} = -31.329 + 0.386\ \mathrm{C} + 1.889\ \mathrm{H} + 0.522\ \mathrm{O} + 0.330\ \mathrm{N} \tag{8}$$

Gautam et al. [92] have proposed another useful relationship:

$$\mathrm{CO} = 0.71\ \mathrm{C} - 1.35\ \mathrm{H} + 0.40\ \mathrm{O} - 22.43 \tag{9}$$

$$\mathrm{H_2} = 0.223\ \mathrm{C} + 1.022\ \mathrm{H} + 0.332\ \mathrm{O} - 15.36 \tag{10}$$

Table 3. Proposed selected biomass for gasification processes

Criteria	First priority	Second priority	Third priority	Fourth priority
Highest H/C ratio	Sawdust	Corn	Palm kernel oil	Wood pellet
Lowest O/C ratio	MSW	Wood pellet	Shell coconut	Sawdust
The most VM and FC	Woodchips	Wood pellet	Sawdust	Palm kernel oil
The most C and O	Woodchips	Shell coconut	Sawdust	Palm kernel oil

The concentrations of CO, CH_4, and H_2 gas increase relative to the concentrations of C and O, as shown in Eqs. (6)–(10). Table 2 shows that biomass materials such as wood char, sawdust, palm kernel oil, coconut shell, and palm kernel have the highest carbon and oxygen concentrations, both above 90%. Sawdust and MSW have the largest quantities of hydrogen in their biomass. However, gasification can create large amounts of syngas from biomass with a carbon and oxygen content higher than 90%. Recommendations for suitable biomasses for gasification, based on biomass qualities, are shown in Table 3.

3.1.1 Reactor gasifier

The gasification process yields syngas of varying quality depending on the reactor utilized. Updraft, downdraft, and fluidized gasifiers are the three distinctive varieties of gasification reactors. [93]. Small to medium-scale gasification systems work best with fixed-bed reactors. Downdraft and updraft reactors are fixed-bed reactors. A throatless downdraft gasifier makes small-scale syngas production system design, manufacture, and testing straightforward. The high carbon conversion rate of this style of gasifier makes it practicable [95]. Small- and medium-sized thermal power plants heat with downdraft gasifiers. This method has a simple design and easy usability but produces some tar [92]. Downdraft reactors have low efficiency, high gas output temperature, limited heat transmission, and the temperature can be difficult to adjust [26,33]. Warm air and reactor integration for gasification, cooling, and cleaning, especially for tar removal, can improve gasifier performance [95].

Using updraft technology, gasification agents transfer oxygen and air upwards while releasing gasification syngas. In comparison, the syngas generated during gasification flows downwards in downdraft types. Downdraft and updraft gasifiers are two names for the same type of fixed-bed technology, which can generate up to 10 MW of heat. [94]. Heating and thermal facilities of smaller and medium sizes often employ downdraft gasifier technology. This approach improves the quality of the syngas, especially its tar concentration, and is easy to implement and use [19]. According to survey data, downdraft gasifiers account for 75% of commercial gasification methods, fluidized beds for 20%, updraft for 2.5%, and other types for 2.5%. [95], [96]. The most recent innovations in gasification technology include the double-stage reactors [20], a variation of three stages of air intake [19], and air preheating [97].

Gasification is a four-step process that begins with drying and continues via pyrolysis, oxidation, and reduction [32], [98]. Figure 3(a) demonstrates gasification in a downdraft reactor. The gasification process results in a downward flow of syngas. Figure 3(b) shows that the gasification process sends updraft syngas upward. Syngas is a by-product of gasification, which involves several chemical reactions. Table 4 displays some of the chemical reactions that happen during gasification.

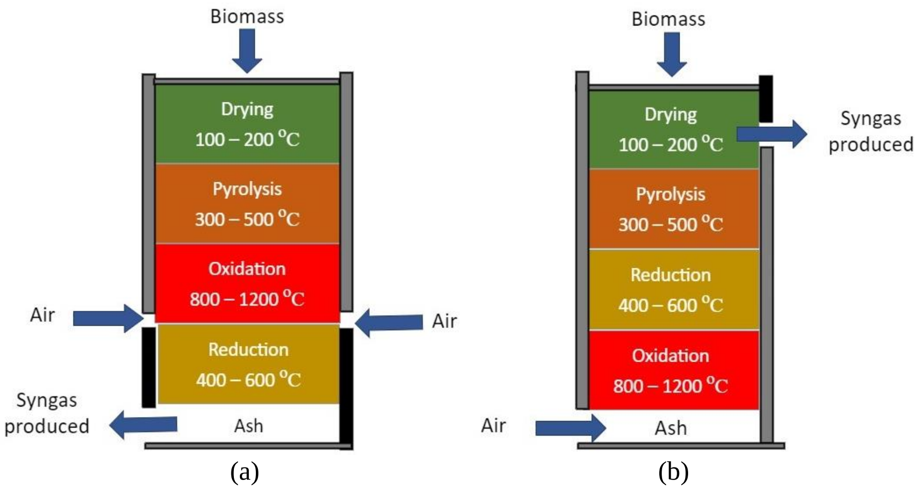

Figure 3. Schematic diagram of the biomass gasification process in (a) downdraft and (b) updraft reactors

Table 4. Chemical reactions and mechanisms of the gasification process

Reaction name	Reaction	Endothermic/ Exothermic	Temperature
Combustion char	$C + O_2 = CO_2$	Exothermic	
Boudouard reaction	$C + CO_2=2CO$	Endothermic	> 700 °C
Water–gas reaction	$C + H_2O = CO + H_2$	Endothermic	> 700 °C
	$C+ 2H_2O = CO_2 + 2H_2$	Endothermic	-
Methane decomposition	$CH_4 + H_2O = CO + 3H_2$	Endothermic	> 500 °C
	$CH_4 + 2H_2O = CO_2 + H_2$	-	
Water–gas shift reaction	$CO + H_2O = CO_2 + H_2$	Exothermic	300–600 °C
Methanation reaction	$CO + 3H_2 = CH_4 + H_2O$	Exothermic	300–600 °C
	$CO + 4H_2 = CH_4 + 2H_2O$	Exothermic	300–600 °C

Source: Watson et al., [98] and Valderama et al.[99]

The quality of syngas gasification is determined by at least three operating conditions: gasifier temperature, equivalent ratio (ER), and steam-to-biomass ratio (S/B) [23], [24], [88]. Table 5 shows how different operating parameters impact gasification.

Table 5. Operating conditions for biomass gasification

Parameter	Observation
Operating conditions	• Gasification partial pressure, heating rate, temperature, and pressure affect syngas yield and composition. • Higher heating rates enhance syngas yield and decrease tar. • High working temperature produces large volumes of H_2 and CO and low tar. • Agricultural waste, RFD, and wood gasification at 750–850, 800–900, and 850–950 °C.
ER	• The gasification and combustion stoichiometric air-to-fuel ratios and the ER are the same. • ER 0.2–0.3 is optimal for air gasification. • ER>0.4 is full combustion; ER = 0.2 is incomplete gasification. • In syngas, ER declines while H_2 and CO increase.ER rises, whereas H_2 and CO fall and CO_2 rises.
Gasification agents	• Gasification of air, oxygen, and steam impacts the characteristics of the resulting syngas. • Gasification with air agents has a heating value between 4 and 7 MJ/Nm^3. • Gasification performed using steam agents produces high levels of CO and H_2, with a high heating value and a low concentration of tar.
Steam to biomass ratio (S/B)	• For gasification steam, an S/B ratio of 0.3 to 1.0 is optimal. • A low tar content and high CO, H_2, and CO_2 concentrations are indicated by a S/B ratio between 1.35 and 4.04.

Source: Ren et al., [23] dan Molino et al., [24]

3.1.2 Effect of ER or S/B and T on yield and LHV of syngas

Syngas produced by air gasification contains CO, H_2, CH_4, CO_2, and N_2. Syngas has a typical volume composition of 15%–30% CO, 10%–25% H_2, 3%–10% CH_4, 5%–15% CO_2, and 40%–55% N_2 [24-26]. The syngas composition affects overall calorific value, combustion efficiency, and combustion system design. Syngas with more CO and H_2 have a higher calorific value. High nitrogen concentrations in power plants and internal combustion engines affect syngas calorific value and efficiency [23]. Tables 6 and 7 summarise studies that considered the effects of temperature, ER, and S/B on the composition and production of syngas using the operating parameters from Table 5. Tables 6 and 7 display the LHV (MJ/Nm^3) of the syngas, which is calculated using the formula [32]:

$$\mathrm{LHV_g} = 0.12622\ \mathrm{CO} + 0.10788\ \mathrm{H_2} + 0.35814\ \mathrm{CH_4} \tag{11}$$

Table 6. Effects of ER, T, biomass type, and air gasification agent on syngas composition and LHV

Biomass	ER	T (˚C)	Gas composition (%vol)			LHV (MJ/Nm^3)	Reference
			CO	CH_4	H_2		
Corn	0.28	874	15.79	3.19	13.27	4.57	[33], [34], [38], [39]
Rice husk	0.36	856	13.69	3.02	7.23	4.53	[40], [42]
MSW	0.31	843	23.79	6.67	18.44	7.38	[32], [46], [47], [48], [49]
Shell coconut	0.22	968	14.50	8.08	26.87	7.62	[51], [53]
Palm kernel oil	0.40	871	20.30	1.40	11.06	4.25	[55], [57]
Sawdust	0.26	779	19.04	4.86	21.56	6.47	[61], [64], [66], [67], [68]
Woodchips	0.30	840	18.75	2.89	11.72	4.66	[70], [71], [72], [73], [75], [76]
Wood pellet	0.22	820	20.30	3.21	14.65	5.29	[32], [76], [79], [80], [81], [82], [83], [84], [85], [86]
Wood char	0.32	845	25.33	2.36	10.19	5.14	[28], [29], [30], [31]

Buragohain et al. [87] have developed a correlation to explain how the operating parameters ER and T affect the yield of syngas and LHV syngas in air gasification:

$$Y_{\mathrm{syngas}} = 1.06T^{-0.104}(AR)^{0.337}(\mathrm{H/C})^{-0.759} \tag{12}$$

$$\mathrm{LHV_g} = 0.936T^{0.114}(AR)^{-0.796}(\mathrm{H/C})^{-0.142} \tag{13}$$

Pio et al. [100] have provided another non-H/C correlation that can be used to examine the effects of ER and T on syngas yield and LHV:

$$Y_{\mathrm{syngas}} = 0.001246\ T + 3.400375\ ER + 0.31634 \tag{14}$$

$$\mathrm{LHV_g} = 0.006549\,T - 12.4161\,ER + 4.339622 \tag{15}$$

Under constant AR and H/C conditions, Eqs. (12)–(13) state that when the temperature increases, the composition of the syngas yield decreases, and the LHV increases. However, the syngas composition will be reduced by the gasification temperature. Similarly, if T and H/C remain constant, increasing the ER will result in higher syngas output. Both the syngas yield and the LHV in the case of ER increase with rising temperature, as shown by Pio et al. [100]. Results from the gasification process confirm this [98]. The phenomena that increase ER cause an oxidation reaction, which raises the temperature, resulting in a binding reaction that can produce CO gas. If the ER decreases, so does the amount of oxygen entering the reactor. An increase in oxygen encourages the oxidation reaction, which produces more heat and raises the temperature. An increase in temperature causes an increase in CO_2, while the CO and H_2 produced decreases. High temperatures cause the equilibrium reaction to shift from an endothermic process (CO_2+H_2=CO+H_2O) to an exothermic reaction (CO+H_2O=CO_2+H_2). Other reactions include the breakdown of CH_4 (Table 4).

Table 6 shows that the highest syngas production uses coconut shell biomass (49.45% vol) at ER = 0.22 and T = 968 °C, MSW (48.90% vol) at ER = 0.31 and T = 843 °C, and sawdust (45.46% vol) at ER = 0.26 and T = 779 °C. The high volume of syngas produced is most likely due to the influence of the gasification temperature factor. The volume of syngas is directly correlated with the LHV of the syngas. The maximum LHVs of syngas were obtained when the air gasification process used coconut shell biomass (7.63 MJ/Nm^3), MSW (7.38 MJ/Nm^3), and sawdust (6.47 MJ/Nm^3). This result is relevant to Eqs. (13) and (15), which state that when the temperature rises and the ER (or AR) decreases, the LHV of the syngas increases. The results of this research are relevant to research from Sansaniwal et al. [10].

3.1.3 Effect of S/B and T on syngas yield and LHV

Table 7 shows the effects of the steam gasification agent (S/B) and the temperature on the yield composition and LHV of syngas. Table 7 shows that gasification with palm kernel oil biomass (85.79% vol) at S/B = 1.51 and T = 741 °C, shell coconut (78.32% vol) at S/B = 0.76 and T = 847 °C, and corn (76.52% vol) at S/B = 0.92 and T = 822 °C results in the maximum volume of syngas yield. Meanwhile, biomass palm kernel oil produces the greatest LHV (11.91 MJ/Nm^3), followed by shell coconut (10.70 MJ/Nm^3) and sawdust (10.66 MJ/Nm^3).

Halim et al. [101] have established a system of equations that explains this behavior, which is:

$$\begin{aligned} Y_{syngas} = -0.11391 + 1.57701\times 10^{-3}T + 0.36540\,(S/B) - 2.5\times 10^{-7}T\,(S/B) \\ -4.43966\times 10^{-7}T^2 - 0.11103\,(S/B)^2 \end{aligned} \tag{16}$$

$$\begin{aligned} LHV_g = -1.65575 + 0.015803\,T + 6.59402\,(S/B) - 1.875\times 10^{-3}\,T\,(S/B) \\ -6.56466\times 10^{-6}T^2 - 1.95034\,(S\,B)^2 \end{aligned} \tag{17}$$

Table 7. Effects of S/B, T, biomass type, and steam gasification agent on syngas composition and LHV

Biomass	S/B	T (°C)	Gas composition (%vol)			LHV (MJ/Nm^3)	Reference
			CO	CH_4	H_2		
Corn	0.92	822	28.94	6.35	41.22	10.38	[34], [36], [37]
Rice husk	1.09	801	23.34	6.70	44.11	10.09	[36], [41], [43]
MSW	1.09	810	23.31	7.16	45.50	10.42	[44], [45], [50], [102]
Shell coconut	0.76	847	35.73	6.39	36.19	10.70	[52], [54]
Palm kernel oil	1.51	742	15.41	9.46	60.93	11.91	[56], [58], [59], [60]
Sawdust	1.14	807	29.06	7.76	39.06	10.66	[61], [62], [63], [65], [69]
Woodchips	0.82	831	25.79	6.78	34.58	9.42	[74], [77], [78]
Wood pellets	0.80	820	23.94	9.51	30.34	9.70	[32], [76], [79], [80], [81], [82], [83], [84], [85], [86]

Table 8. Proposed biomass, air, and steam gasification operating conditions for optimum syngas yield and LHV

Gasification	Biomass and operating conditions			
	First priority	Second priority	Third priority	Fourth priority
Air gasification, maximum syngas yield and LHV	Shell coconut T=868 °C ER=0.22	MSW T=843 °C ER=0.31	Sawdust T=779 °C ER=0.26	Wood pellet T=820 °C ER=0.22
Steam gasification, maximum syngas yield and LHV	Palm kernel oil T=741 °C S/B=1.51	Sawdust T=807 °C S/B=1.14	MSW T=810 °C S/B=1.09	Shell coconut T=847 °C S/B=0.76

According to Eq. (16) and (17), under constant S/B conditions, the volume yield and LHV of syngas will be maximized at a specific temperature. The syngas yield volume at T = 742 °C is the highest. This suggests that when the temperature rises, the syngas volume decreases. Similarly, under constant temperature conditions, the volume yield and LHV of syngas will peak at a specific S/B. Furthermore, if S/B is less than 1.51, the LHV of the syngas will decrease. Considering the combination of T and S/B for the steam gasification process, the biomasses that produce the highest yield and lowest LHV of syngas are MSW, palm kernel oil, and sawdust. Table 8 provides a list of potential biomass types and operating parameters for producing syngas for use in dual-fuel applications.

3.2 Syngas Dual-fuel Internal Combustion Engine

Biomass is a potential source of new renewable energy fuels. Current commercial biomass energy sources include ethanol, biodiesel, and methanol. Ethanol, methanol, and biodiesel must be mechanically converted. The thermochemical technique produces syngas as an energy source [103]**.** Syngas is currently in the research and development stage. Countries that have effectively implemented energy diversification strategies include the United States and Brazil, which have used bioethanol as an additive in automobile gasoline. In 2018, the United States produced 16.1 billion gallons of bioethanol; Brazil produced 7.95 billion gallons. Most vehicles in Brazil are flexible-fuel vehicles that have been converted to consume pure bioethanol. Since 1976, the Brazilian government has mandated that ethanol be used in a vehicle fuel blend of 22% ethanol and 78% gasoline, known as E22. This ratio increased in 2015 when Brazil began using bioethanol at a ratio of 25% ethanol and 75% gasoline (E25) [104].

Diesel (biodiesel) fuels industrial engines, whereas gasoline fuels most car engines and diesel fuels large-capacity engines. Biofuels are being promoted in the transportation industry, emphasizing renewable energy sources, sustainable development, green energy, and environmental friendliness [105]**.** The physical qualities of biodiesel, bioethanol, and gasoline distinguish industrial engine fuel from automobile fuel. One advantage of bioethanol is that it improves engine performance at high engine speeds. Bioethanol can also help to cut CO_2 emissions. Disadvantages include the interaction of bioethanol with metals such as magnesium and aluminum. Biofuel is one type of biomass used to fuel other energy sources. Biofuels are composed of biogas, biomethane, and syngas [106].

Internal combustion engines (ICE) can be divided into spark ignition engines and compression ignition engines. According to numerous articles in reputable journals, syngas has not been standardized as a fuel for internal combustion engines. Biodiesel, bioethanol, and bio-methanol are produced from biomass and are commercially viable fuels for vehicles [106], [107]. Syngas is adaptable and may be used for many different purposes. It can generate electricity, heat and power systems, fuel transportation, gas turbines, ICE, and integrated gasification combined cycles. [108]. However, syngas cannot currently be sold as a motor fuel. Advanced technology is still required to transform syngas into liquid form, including Fischer–Tropsch reactor (FT) technology [107].

Using syngas in ICE can be challenging due to its variable calorific value, high tar content, inefficient carbon conversion, pollutant emissions, and engine modifications. CO, CH_4, and H_2 levels affect syngas calorific value. Tar, which settles in the combustion chamber, is another issue. To address this, syngas tar must be cleared. The high H_2 content in syngas causes quick combustion and knocking, while excessive CO delays combustion. Variations in combustion require optimal ignition settings. Therefore, engine modifications are necessary, particularly in the gasoline filling system, injection, and ignition control. Table 9 displays the search results for papers published between 2010 and 2023 with keywords associated with using syngas as fuel in direct injection or compression injection ICE. Summary results are presented in four categories: gasification and syngas, engine, engine performance, and emissions.

Table 9. Syngas, a dual-fuel option for ICE, engine modification, performance, and emission reduction

Biomass, Reactor LHV Syngas (MJ/Nm^3)	Engine Cylinder Power-rpm Modified Compression ratio	Brake power, SFC (kg/kWh), engine efficiency fuel savings	HC	CO	NOx	CO_2	Reference
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
n.a. $CO+H_2$ 14.81 (MJ/kg)	DI Diesel engine 1-cylinder 5.2 kW, 1500 rpm Gas mixer valve 17.5:1	80% load n.a. 16.1 (20.92) 58.77 % save	45 (26) ppm	240 (140) ppm	104 (144) ppm	n.a.	[109]
Woodchips Downdraft 4.51–4.53	Gas engine, 6-cylinder, 120 kW, 1500 rpm Intake manifold n.a.	100 kW, 1.36 kg/kWh 25% n.a.	n.a.	n.a.	n.a.	n.a.	[110]

Table 9. (cont.)

Biomass, Reactor LHV Syngas (MJ/Nm^3)	Engine Cylinder Power-rpm Modified Compression ratio	Brake power, SFC (kg/kWh), engine efficiency fuel savings	HC	CO	NOx	CO_2	Reference
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
n.a. $CO+H_2$ 10.11–23.09 (MJ/kg)	DI Diesel engine 1-cylinder 5.2 kW, 1500 rpm Gas mixer, valve 17.5:1	80% load 19 (17.8) fuel 19 (20%) eff n.a.	n.a.	n.a.	n.a.	n.a.	[17]
n.a.n.a. $CO+H_2$ 10.11–23.09 (MJ/kg)	DI Diesel engine 1-cylinder 5.2 kW, 1500 rpm Gas mixer, valve 17.5:1	80% load n.a. n.a. 60% save	115 (40) ppm	240 (60) ppm	125 (225) ppm	n.a.	[111]
Sawdust Downdraft 4.4	Natural gas n.a. 100 kW, 1500 rpm None n.a.	98 kW 5.7(4.5) kg/kWh n.a. n.a.	n.a.	n.a.	n.a.	n.a.	[112]
Woodchips Downdraft 5	Diesel, 1-cylinder, 4.4 kW-1500 17.5:1	4.4. kW 17.3 (13.5) fuel MJ/kWh 22.5 (25.6%)	21 (16) ppm	0.0328 (0.024) %	225 (435) ppm	n.a.	[113]
Wood Downdraft 4.59–4.61	Diesel, 6-cylinder, 68.4 kW, 1800 rpm Intake manifold 17.5:1	50 kW 1.0 kg/kWh, 26.8%, 78.7%	n.a.	38.5 (14.0) g/kWh	1.19 (2.63) g/kWh	n.a.	[114]
Wood chips Downdraft 5.6	Natural gas, 6-cylinder, 100 kW, 1500 rpm Intake manifold n.a.	73 kW 3.21 kg/kWh 21 % eff n.a.	n.a.	n.a.	n.a.	n.a.	[115]
Charcoal Downdraft 4.2–4.6	Diesel, 1-cylinder 5.88 kW, 2400 rpm Intake manifold 18:1	n.a., 14.5 (10.2) 25% (34%), 43% save	n.a.	0.38 (0.04) %	n.a.	n.a.	[116]
Wood (Japotra) Downdraft 5.885	Diesel engine 1-cylinder 7.5 kW,1500 rpm n.a. 17.5:1	n.a. 25 (20) fuel MJ/kWh) 17 (22 %) eff n.a.	58 (45) ppm	1.96 (1.45) (%)	125 (200) ppm	11.2– 12.3 (%)	[117]
n.a. $CO-H_2-CH_4$ 4.7–7.4	Diesel 1-cylinder 37 kW, 3000 rpm Intake manifold 17.6:1	n.a. n.a n.a n.a	2000 (1000) ppm	2250 (750) ppm	175 (325) ppm	6.5 (%)	[118]
Charcoal Downdraft 4.64	CI diesel engine 1-cylinder 8.2 kW, 1800 rpm Combustion chamber 17:1	4.2 kW 2.77 (2) 23.5 (26.9 %) n.a.	10 (8.5) ppm	0.4 (0.34) (%vol)	n.a.	n.a.	[119]

Table 9. (cont.)

Biomass, Reactor LHV Syngas (MJ/Nm^3)	Engine Cylinder Power-rpm Modified Compression ratio	Brake power, SFC (kg/kWh), engine efficiency fuel savings	HC	CO	NOx	CO_2	Reference
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
n.a. $CO-H_2-CH_4$ 4.06–10.29	Diesel 1-cylinder 74.6 kW, 2100 rpm Intake manifold 16.25:1	n.a. n.a. 35 (42.5%) n.a.	n.a.	63 (42) g/kWh	5.5 (7.9) g/kWh	0.03-0.05 g/kWh	[120]
Rice bran Downdraft 5.6	Diesel, 1-cylinder, 3.7 kW, 1500 rpm n.a. n.a.	2.96 kW 6.78 kg/kWh 18.9% n.a	50 (20) ppm	4000 (3000) ppm	400 (1000) ppm	n.a.	[121]
Choir pith Downdraft 6.549	DI diesel engine 2-cylinder 11.9 kW, 1500 rpm 16:1	10 kW n.a. n.a. 54–88% save	66 (44) ppm	0.66 (0.45) %	55 (173) ppm	6.24 (5.34) %	[122]
Rice husk Downdraft 6.01	DI diesel engine 2-cylinder 14 kW, 1500 rpm n.a. 16:1	10 kW 25 (17.6) MJ/kWh) 22–25 (27%) 45%–60% save	30 (10) ppm	0.29 (0.22) %	126 (526) ppm	5.7 (2.89) %	[123]
Switchgrass Downdraft 6.4–6.54	Natural gas, 2-cylinder, 10 kW, 3600 rpm fuel venturi n.a.	5 (7) kW, 1.97 (1.3) n.a. n.a. n.a.	1843 (1262) ppm	17250 (7250) ppm	25.9 (0.001)	79000 (149000) ppm	[124]
MSW Downdraft 6.7–7.7	Natural gas, 2-cylinder, 10 kW, 3600 rpm Air fuel intake n.a.	5.7 kW 3.33 (3.0) 19.5%–22% n.a	90 (n.a.) ppm	16533 (2867) ppm	4.4 (27.3) ppm	33785 (68367) ppm	[125]
MSW Downdraft 3.3–4.0	Diesel, n.a. Intake manifold n.a.	3 kW, 0.29 (0.17) n.a. 44%–56% save	n.a.	n.a.	n.a.	n.a.	[126]
Red oak Downdraft 5.1–6.0	Gasoline, 4-cylinder, 28.3 kW, 1800 rpm Engine control module n.a.	23.1 kW n.a., 25.6% n.a.	n.a.	n.a.	n.a.	n.a.	[12]
Wheat straw Downdraft n.a.	Diesel, 1-cylinder 3.5 kW,1500 rpm Intake manifold 18:1	3.0 (3.5) kW, 2.35 (2.25) 26.19 (35.89%) 76.74% save	2000 (500) ppm	495 (200) ppm	25 (85) ppm	n.a.	[127]
Wood pellets Downdraft 4.54–4.88	Diesel, 1-cylinder 3.5 kW,1800 rpm Intake mixing chamber 17.5:1	3.40 kW, 1.59 (1.28) 22.54 (30.51%) n.a	n.a.	n.a.	319.09 (420.07) ppm	n.a.	[128]
Forestry biomass CO-CH4-H2 4.96	Natural gas 4-cylinder 42 kW, 2570 rpm Venturi gas mixture n.a.	27 kW n.a. 27.5% eff	0.36 (0.22) g/kWh	1.69 (1.12) g/kWh	2.85 (3.54) g/kWh	135.6 g/kWh	[129]

Table 9. (cont.)

Biomass, Reactor LHV Syngas (MJ/Nm^3)	Engine Cylinder Power-rpm Modified Compression ratio	Brake power, SFC (kg/kWh), engine efficiency fuel savings	HC	CO	NOx	CO_2	Reference
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
n.a. Downdraft 4.2–4.8	Diesel engine 3-cylinder 120 kW, 3750 rpm Intake mixing 17.5:1	n.a. n.a. 36 (40%) n.a.	n.a.	340 (200) (gr/kWh)	0.8 (1.1) gr/kWh)	n.a.	[130]
n.a. n.a. 3.6–5.3 (MJ/kg)	Diesel engine 4-cylinder 36. kW, 1800 rpm Intake mixing 17.5:1	11 kW n.a. 38%–40% eff 32.5% save	0.0131 (0.0125) g/kWh	79.8 (63.4) g/kWh	5.6 (8.9) (g/kWh)	820 (908) g/kWh	[131]
Wood Downdraft 6.415	Gas engine 6-cylinder, 115 kW, 1500 rpm Gas mixer n.a.	89 kW 5.2 (1.86) n.a. 86.41%	213 (72) mg/Nm^3	n.a.	n.a.	n.a.	[132]
Wood pellets Downdraft n.a.	CI Diesel 1-cylinder 3.9 kW, 3600 rpm Intake manifold 20:1	3 kW n.a. n.a n.a	n.a.	0.6 (%vol)	138.6	13.5 (%vol)	[133]
Forest waste MSW Downdraft 6.03–6.16	Diesel, 2-cylinder, 7.5 kW, 5000 rpm Intake manifold n.a.	5.71 kW, 1.08 g/L n.a. 20.89% save	n.a.	n.a.	n.a.	n.a.	[18]
Bamboo Downdraft 5.85	Natural gas 6-cylinder, 241 kW, 6000 rpm n.a.	223 kW, 0.0159 (0.0128) 31.7 (38.6%) n.a.	n.a.	n.a.	n.a.	n.a.	[134]

3.2.1 Biomass, gasification reactors, and LHV syngas

Diesel fuel is a blend of $C_{12}H_{24}$, $C_{16}H_{34}$, and C_6H_4, whereas syngas is composed of CO (15%–30%), H_2 (10%–25%), and CH_4 (3%–10%). Diesel fuel has a higher calorific value (42–46 MJ/kg), while syngas has a lower value (4–12 MJ/Nm^3). Because of its high calorific value, diesel is an excellent fuel for internal combustion engines. Due to their chemical makeup, long-chain hydrocarbons are exceptionally efficient heat producers when burned, and this is where their great energy originates from. Diesel comprises liquid long-chain hydrocarbons, whereas syngas is mostly gaseous, including CO, H_2, and CH_4. Consequently, the energy values, combustion characteristics, and effects on the environment of the two fuels are very different [123-124].

Column (1) of Table 9 shows the type of biomass, gasification reactor, and syngas produced. Biomass utilized as raw material includes wood chips, sawdust, charcoal, MSW, and wood pellets. Research utilizing MSW and wood chips has increased recently. Downdraft gasifier reactors are the majority of the reactors that have been deployed. A downdraft reactor is the best approach when gasifying biomass for ICE. The downdraft reactor is an easy-to-assemble device that produces a low tar content (0.015 to 3.0 g/Nm^3) and a high carbon conversion efficiency [135]. These reactors are relatively straightforward to clean [13], [98]: tar levels in syngas can be lowered by combining the gasification and tar removal operations in the reactor [136].

Syngas, used as a dual fuel, results from gasification, producing a mixture of gases such as H_2, CO, and CH_4. Gas generators that use biomass gasification produce syngas with a calorific value of 3.6–7.7 MJ/Nm^3. Syngas with a calorific value between 4.06 and 23.09 MJ/kg is produced from H_2, CO, and CH_4. Paykani et al. [108]] have found that syngas has a heating value ranging from 5.02 to 12.57 MJ/Nm^3. The LHV of syngas is determined by the CO_2 and H_2 levels of the gas generator [32]. The LHV value for CO-H_2-CH_4 gas ranges from 15.7 to 24.4 MJ/kg, while that for gas producers ranges from 5.02 to 7.47 MJ/kg [108].

3.2.2 Engines and engine modifications

Some modifications are necessary to ensure that diesel engines can operate on syngas, which have significantly different physical and chemical properties compared to liquid diesel. These modifications make syngas a more efficient fuel, whether combined with other fuels or on its own. Syngas can be used in diesel engines by modifying the air-fuel intake system. When installed in the air duct, a carburetor or gas injector allows the management of the air-fuel ratio [129,130]. Second, the ignition system must be modified because diesel engines use the principle of high compression, whereas syngas has a higher ignition temperature. Installing an ignition spark plug necessitates an additional ignition system [131-133]. Finally, syngas combustion generates heat, necessitating the addition of an intercooler or additional cooling system [108,117].

In Table 9, column (2) outlines the engine types and modifications employed in dual-fuel research for heat generation. The engine types employed in the study were diesel (71.43%), gasoline (28.57%), and natural gas (28.57%). In a dual-fuel system, engine modifications are performed prior to usage. Engine modifications include changes to the combustion chamber, combustion system, compression ratio, and air duct for blending syngas and fuel. The compression ratio is adjusted by decreasing the number of cylinder heads. A six-cylinder diesel engine is converted into a single-cylinder engine by eliminating the need for additional heat cylinders.

Small machines need less than 10 kW of engine power (60%), medium use 10–100 kW (20%), and large use more than 100 kW (20%). The engine speed at 1500 rpm is 46.43%, while the speed at 1800 rpm is 53.57%. Diesel engine compression rates less than 17.5:1 are 11.76%, while others are 88.24% of the engines studied. The compression ratio is 17.5:1. This indicates that limited power, a low engine rpm, and a high compression ratio are employed. These findings are similar to those published by [12], [14], [137].

3.2.3 Brake power, SFC, and thermal efficiency

Column (3) of Table 9 shows how the brake power, specific fuel consumption (SFC), thermal efficiency, and fuel savings affect dual fuel. “Brake power” refers to the maximum power the generator produces during operation. The brake power (P-kW) is determined using the formula [131]:

$$P = 2\pi N\tau \tag{18}$$

where N represents the number of engine speeds (Nm^3), and τ is the engine speed. Another aspect of the performance of the dual-fuel system to consider is the SFC, also known as the thermal efficiency of the system. SFC measures the electricity produced as a percentage of the fuel used (kg). One application of the SFC is evaluating the effectiveness of power generation and fuel usage.[124]. The SFC is determined using the following formula [124], [132]:

$$SFC = \frac{m_f}{P} \tag{19}$$

where m_f is the fuel consumption rate in kilograms per hour, and P is the total power output of the generator in kilowatts. The capacity of a machine to transform thermal energy into mechanical energy is called its thermal efficiency. The thermal efficiency of a system, also known as overall efficiency or brake thermal efficiency (η_T-%), is determined using the formula [119], [132]:

$$\eta_T = \frac{P}{m_f HHV_f} \tag{20}$$

When the power output data (Table 9 column 2) and brake power data (Table 9 column 3) are compared, it is obvious that using syngas as a fuel results in derating, increased SFC, decreased thermal efficiency, and savings in diesel or gas fuel. The average derating while using syngas instead of diesel engines at 1500 rpm is 17.70%. The average derating at engine speeds equal to 1800 rpm is 27.90%, whereas at speeds greater than 1800 rpm, it is 29.08%. Meanwhile, for syngas substitution in gas engines, the average derating is 27.0% between 1500 and 1800 rpm and 21.04% above 1800 rpm. According to these numbers, derating was highest at very high diesel engine speeds, while using syngas to replace derating gas was the lowest. Therefore, gas engines will work better using syngas instead of natural gas. The results obtained here are in accordance with those of Martines et al. [137]] and Nayak et al.[122].

Using syngas reduces diesel or natural gas use, leading to lower fuel consumption, as shown in Table 9, column (3). The brake power and rpm determine the SFC. At 1500 rpm, the average SFC rose by 26.58% to 3.04 kg/kWh. The SFC increased by 38.42% at 1800 rpm for diesel engines, from 1.2 kg/kWh to 1.64 kg/kWh. Meanwhile, at diesel engine speeds greater than 1800 rpm, the SFC rose by 40.04%, from 1.26 kg/kWh to 1.77 kg/kWh. Syngas substitution with natural gas boosted the average SFC from 1.68 kg/kWh to 2.76 kg/kWh. The impact of rising SFC is decreasing thermal efficiency. These findings are relevant to previous research conducted by Indrawan et al. [12]] and Fiore et al. [14]. At 1500, 1800, and over 1800 rpm, syngas thermal efficiency in diesel engines declines to 20.66%, 28.24%, and 29.88%, respectively. Using syngas in gasoline engines as a dual fuel also lowers the thermal efficiency. A dual-fuel gas engine has an average thermal efficiency of 25.06%, which is lower than that of a gas engine (35.6%). This is pertinent to the research of Indrawan et al. [12]] and Martines et al. [137]. Employing syngas instead of diesel or gas fuel reduces the amount of diesel or natural gas fuel consumed. The average savings from using diesel fuel was 55.88%, while natural gas savings reached only 39.52%.

3.2.4 Emissions and particulates

One factor to consider is the utilization of syngas as an alternative fuel, particularly with respect to particles and emissions from engine exhaust gas. Emissions are combustion gases emitted into the atmosphere. In compliance with EU regulations, detected emissions include HCs, CO, CO_2, and NOx gases. Meanwhile, particulates are solid particles formed during incomplete combustion in the combustion chamber. Several criteria can be used to limit emissions and particles from combustion products. Standards from the EU (Stage V), USA EPA, and China [138], [139], [140]] can be used to assess the impact of using syngas in ICE. There are many advantages to using biomass, including decreasing our dependency on fossil fuels, boosting the use of renewable energy sources, decreasing greenhouse gas emissions, and reducing air pollutants such as SOx and NOx. Due to plant absorption of CO_2 emissions, using syngas as a fuel does not contribute to global warming. One possibility is using the gasification process, which converts MSW, agricultural by-products, and forest debris into energy. The use of syngas from biomass increases sustainability by lowering the emissions of pollutants and greenhouse gases, which benefits the economy and the environment.

The gas and particle emissions from using syngas in ICE are shown in columns (4)–(7) of Table 9. Information on emissions and particles is omitted from some studies. There is currently no universally accepted unit of emission measurement: parts per million, kilograms per thousand kilowatt-hours, or percentages are all used. Table 9, columns (4)–(7), shows that HC and CO emissions increase while NOx and CO_2 emissions decrease when syngas is used as a substitute for fossil fuels. Nitrogen oxides, primarily NO_2 and NO, as well as CO, particulate matter (PM), and SOx, are all released into the atmosphere by syngas engines that run on ICE. NOx causes acid rain, while CO pollution harms human health. Unburned hydrocarbons generate toxic tropospheric ozone and acid rain, both detrimental to human health. NOx, CO, UHC, PM, SOx, and NH_3 are the primary pollutants emitted when ICE uses syngas. Even though syngas is cleaner than fossil fuels, emission management must be implemented.

These findings are pertinent to previous studies by Teoh et al. [16], Indrawan et al. [12], and Hamid et al. [141]. According to other research, utilizing syngas in gasoline-powered engines reduces NOx and SO_2 while increasing the gas concentration in the exhaust gas [16], [141].

3.2.5 Tar and syngas cleaning

The increased tar content caused by using syngas instead of fossil fuels negatively impacts engines, including corrosion and plugging. [137], [142]. Table 10 provides suggestions on how to cope with these concerns, such as tar when using syngas for internal combustion [137], [142]. Several technologies and their efficiencies can be utilized to remove tar, such as spray towers (11%–25%), Venturi scrubbers (50%–90%), Venturi and spray scrubbers (83%–90%), Venturi and cyclone demisters (93%–99%), and vortex scrubbers (67-78%) [143]. The latest technological advancement is incorporating tar delivery into the gasification process. Studies have shown that syngas can be used as a renewable energy source to power engines instead of fossil fuels.

Table 10. Pollutants from syngas internal combustion, an adaptation of Martinez et al. [137] and Cortazar et al. [142]

Pollutants	Source	Potential issues	Method for controlling and reducing
Particulate pollutants	Ash and bed material	Pollution of the environment, agglomeration, and fouling	Scrubber for gas cleaning and filtration
The ash contains alkali metals, such as potassium and sodium	Ash	Corrosion	Cooling, condensation, filtration, adsorption
Nitrogen compounds (NOx, NH_3, HCN)	Nitrogen reaction	Corrosion, environmental pollutant	The procedure of treatment makes use of pure oxygen
Chemicals containing sulfur and chlorine (HCl, H_2S)	Hazardous sulfur and chloride reaction	Corrosion, environmental pollutant	Cleaning with $CaCO_3$, $MgCO_3$
Tar	Low-temperature process	Corrosion and fouling	Removal and cracking

4. CONCLUSIONS AND RECOMMENDATION

Syngas produced by biomass gasification is a novel, renewable energy source for internal engines. Gasification is an effective method for the energy conversion of nine distinct types of biomass. A decrease in biomass moisture content and an increase in carbon value can be achieved through preheating and combination procedures. The downdraft gasifier gasification technique is commonly utilized in gasification operations with an internal engine. Air gasification yields lower heating values than steam gasification. Most dual-fuel studies have used ICE, the most popular of which are diesel and gas engines. Intake manifold modifications for syngas mixing, compression ratio modifications, and air mixtures for the combustion chamber are the most typical. Using a mixture of dual-fuel syngas–diesel or syngas–natural gas will derate the engine, reduce thermal efficiency, increase SFC, and save money. The use of dual fuels reduces CO_2 and NOx emissions while increasing HCs and CO. Tar and gas emissions from the biomass gasification process can cause engine damage and corrosion.

Overall, the present and future possibilities for the development of syngas for ICE have been thoroughly discussed in this paper. Some examples include improving the efficiency of cold gasification, utilizing steam as a gasification agent, including tar purification in the gasification reactor, and powering internal combustion engines with full syngas. The proper way for motorized vehicles to store syngas is an essential consideration. If gasification syngas is to be used in motorized vehicles, its conversion using the Fischer–Tropsch method should be seriously examined.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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