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Review

The Effects of Biosyngas and Biogas on the Operation of Dual-Fuel Diesel Engines: A Review

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Abstract

To address the dual challenges of fossil fuel depletion and environmental pollution, developing clean, renewable alternative fuels is an urgent need. Biomass gas, including biomass syngas and biogas, offers significant potential as an internal combustion engine alternative fuel due to its widespread availability and carbon-neutral properties. This review summarizes research on biomass gas application in dual-fuel diesel engines. Firstly, biosyngas and biogas production methods, characteristics, and purification needs are detailed, highlighting gas composition variability as a key factor impacting engine performance. Secondly, dual-fuel diesel engine operating modes and their integration with advanced low-temperature combustion technologies are analyzed. The review focuses on how biomass gas affects combustion characteristics, engine performance, and emissions. Results indicate dual-fuel mode effectively reduces diesel consumption, emissions, while its carbon-neutrality lowers life-cycle CO_2 emissions and generally suppresses NO_x formation. However, challenges include potential BTE reduction and increased CO and HC emissions at low loads. Future research should prioritize gas quality standardization, intelligent combustion system optimization, and full-chain techno-economic evaluation to advance this technology. Overall, this review concludes that dual-fuel operation with biomass gases can achieve high diesel substitution rates, significantly reducing NO_x and particulate matter emissions. However, challenges such as decreased brake thermal efficiency and increased CO and HC emissions under low-load conditions remain. Future efforts should focus on gas composition standardization, intelligent combustion control, and system-level optimization.

Keywords: biosyngas; biogas; dual-fuel diesel engine; combustion characteristics; emission characteristics

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1. Introduction

With the continuous growth of global energy demand and the progressive depletion of fossil fuel resources, energy security and environmental pollution have emerged as the major challenges facing humanity in the 21st century [1]. Conventional internal combustion engines (ICEs), which rely heavily on petroleum-based fuels, not only lead to substantial greenhouse gas emissions and exacerbate global climate change but also cause a series of environmental and health issues. The transportation and power generation sectors are the primary sources of harmful emissions such as carbon dioxide (CO_2) and nitrogen oxides (NO_x) [2,3]. Therefore, the development of clean, renewable, and low-carbon alternative fuels has become an urgent requirement for the global energy transition [4].

Biomass energy originates from various sources, including agricultural and forestry residues (such as straw and wood chips), dedicated energy crops, and urban organic waste [5]. Beyond the inherent benefits of wide availability, carbon neutrality, and sustainability, the utilization of biomass often leads to low ash content and low sulfur emissions compared to fossil fuels [6]. Crucially, leveraging biomass, particularly residues and organic waste, effectively contributes to waste reduction and resource recovery, thereby enhancing the overall reliability of the energy system [7–9]. Furthermore, biomass is characterized by favorable fuel properties, such as high volatile matter content and enhanced energy density, demonstrating great potential to substitute traditional fossil fuels [10]. To efficiently harness this potential, biomass must often undergo conversion processes. Among various conversion technologies, the thermochemical and biochemical pathways yielding high-quality gaseous fuels, including biosyngas and biogas, have garnered significant attention. These gases can be used not only for power generation and heating but also as fuels for ICEs, particularly showing promising application prospects in dual-fuel (DF) systems when combined with diesel engines [11].

Biosyngas is mainly produced via gasification technology, with hydrogen and carbon monoxide as its principal combustible components, whose composition can be optimized by adjusting the gasification process. In contrast, biogas originates from the anaerobic digestion of organic waste, consisting mainly of methane (CH_4), with higher impurity content but relatively easy purification [12]. Both gases can partially replace diesel in dual-fuel diesel engines, thereby reducing dependence on fossil fuels and significantly lowering pollutant emissions [13].

In recent years, research efforts focusing on biosyngas and biogas have expanded significantly beyond their standalone application in dual-fuel engines. A major trend involves blending these biomass gases with other renewable fuels, such as hydrogen (H_2), or incorporating them into hybrid fuel strategies alongside low-carbon liquid fuels (e.g., biodiesel) to further optimize combustion and emissions [14–16]. Studies have increasingly explored innovative control strategies—such as exhaust gas recirculation (EGR), compression ratio, and fuel injection parameter tuning—to manage the challenges posed by the variable quality of biomass gases and to achieve high efficiency under diverse operating conditions [17–19]. This growing body of work underscores the rapid advancements and sustained interest in maximizing the potential of biomass gases for decarbonizing the transport and power sectors.

The DF diesel engine system introduces gaseous fuels into the intake air, with a small amount of diesel serving as the ignition source, achieving an efficient and cleaner combustion process [20]. This system retains the advantages of diesel engines, such as high compression ratio and high thermal efficiency, while offering fuel flexibility, lower emissions, and relatively low retrofit costs. Consequently, it is particularly suitable for applications in stationary power generation, marine propulsion, and heavy-duty transportation [21–23].

However, due to the complex and variable composition of biomass gases, their combustion characteristics differ significantly from conventional diesel. Practical applications still face multiple challenges, including unstable combustion, reduced thermal efficiency, and difficulties in controlling NO_x and unburned hydrocarbon (UHC) emissions [24–26]. Therefore, systematic research on the combustion characteristics, emission behaviors, and optimization strategies of biomass gases in DF diesel engines is of great significance to promote their large-scale application.

The literature search for this review was conducted across major academic databases, including Elsevier's ScienceDirect, Scopus, and Google Scholar, covering studies published from 2015 to the present concerning the effects of biosyngas and biogas on dual-fuel diesel

engines. Key search terms utilized combinations of words such as 'dual-fuel diesel engine', 'biogas', 'biosyngas', 'combustion', 'performance', and 'emissions'. Article selection was primarily based on their focus on experimental or theoretical investigations of dual-fuel compression-ignition engines using biomass-derived gaseous fuels. Studies involving entirely different engine types or conference abstracts lacking experimental details were excluded. Extracted data included essential parameters such as fuel composition, engine test conditions, and reported performance and emission results.

The innovation of this review lies in its systematic comparison of biosyngas and biogas performance in dual-fuel diesel engines, the integration of advanced combustion strategies such as RCCI and PPCI, and the establishment of a comprehensive analytical framework that spans from gas production and engine adaptation to system-level optimization.

This review aims to systematically summarize the preparation methods and physicochemical properties of biosyngas and biogas, as well as their current applications in DF diesel engines, analyzing their effects on engine performance and emission characteristics, with the goal of providing insights for further research and engineering applications in this field.

2. Biomass Gases

2.1. Biosyngas (and Producer Gas)

Biosyngas, a combustible gas mixture mainly produced through biomass thermochemical gasification technology, originates from renewable biomass feedstocks and holds unique advantages in achieving energy transition and carbon neutrality goals. In addition, some scholars also categorize the gases obtained from pyrolysis processes under the definition of syngas [27].

The feedstock sources of biosyngas are highly diverse, including lignocellulosic biomass (such as wood, straw, and crop residues), agricultural waste (such as animal manure), municipal organic waste, and specially cultivated energy crops [28–30]. Among them, lignocellulosic biomass is regarded as the primary feedstock due to its abundant availability. The wide availability of feedstocks ensures the sustainability and regional adaptability of biosyngas production [31].

Biosyngas is produced through thermochemical gasification, in which solid biomass is converted into syngas under high temperature and oxygen-limited conditions. Commonly used gasifiers include fixed-bed, fluidized-bed, and entrained-flow types [32]. To obtain high-quality biosyngas without nitrogen dilution, pure oxygen (O_2) and/or steam (H_2O) are typically employed as gasifying agents [33].

When air is used as the gasifying agent, the resulting gas is referred to as producer gas [34]. This technology has a long history and was once used as an important alternative fuel for vehicles, power generation, and heating during periods of fossil fuel scarcity, such as in the case of wood gas. Although it has a relatively low calorific value, producer gas still retains certain application value in modern renewable energy systems.

Producer gas is generated via air gasification, where solid carbonaceous feedstocks are converted into combustible gases under high temperature and limited air supply. Common types of gasifiers include updraft fixed-bed, downdraft fixed-bed, and fluidized-bed gasifiers [35–37]. Among them, the downdraft fixed-bed gasifier is more widely applied in biomass gasification because it can effectively crack part of the tar content [38].

The compositions of biosyngas and producer gas are presented in Table 1. The main components of biosyngas are hydrogen (H_2) and CO [39]. In addition to these, biosyngas generally contains varying proportions of CO_2, CH_4, and nitrogen (N_2), as well as water vapor and trace impurities such as sulfur compounds, tar vapors, and particulates. Its spe-

cific composition is not fixed but strongly dependent on biomass feedstock type, gasifying agent selection, and operating parameters of the gasification process [40,41].

The combustible components of producer gas are similar to those of biosyngas, but it typically contains a large amount of non-combustible nitrogen [42,43], which directly results in a significantly lower calorific value. Its composition is also highly dependent on feedstock type, gasifier design, and operating conditions [44].

Table 1. Typical composition and LHV of biosyngas and producer gas.

Biomass	Gasifier Type	Gasifying Agent	Species (vol.%)				LHV (MJ/Nm^3)	Ref.
			H_2	CO	CH_4	CO_2		
coconut shell	downdraft fixed bed	air	18.84	23.02	1.13	7.05	5.35	[45]
oil palm fronds	downdraft	air	9.37	15.27	8.78	15.03	6.62	[46]
samanea saman twig	updraft	compressed air	7.33	30.3	1.2	8.75	5.13	[47]
prosopis juliflora wood	downdraft	N/A	11.08	17.44	4.03	2.43	4.75	[48]
municipal solid waste	downdraft	air	23.8	21.5	3	5.8	5.77	[49]
torrefied rice husk & north east indian coal	dual fluidized bed gasifier	air	22.1	24.6	7.2	16.8	8.1	[50]
sugarcane bagasse	microwave-assisted chemical looping gasification system	air	34.18	36.19	5.6	11.42	16.31 (HHV)	[51]
rice husk	two-stage fixed-bed reactor system	steam	33.58	31.86	11.93	20.38	-	[52]

The variability of biosyngas and producer gas composition is one of the key factors that must be considered when applying them in ICEs [53]. Crude syngas produced directly from gasifiers cannot be used in diesel engines without purification. The purpose of gas cleaning is to remove impurities that would otherwise cause severe damage to engine operation, mainly including tar, dust, sulfur compounds, and chlorides [54].

Due to the high diffusion coefficient and fast flame propagation speed of hydrogen, its proportion directly affects ignition delay and combustion stability. Traditional biosyngas, with relatively low hydrogen content, often exhibits poor ignition and insufficient combustion rates [55]. To address this issue, researchers have proposed hydrogen-enriched biosyngas by optimizing steam gasification, catalytic gasification, and water–gas shift reactions to adjust the CO/H_2 ratio, thereby increasing the hydrogen concentration and significantly improving combustion performance [56].

2.2. Biogas

Biogas is a combustible gas mixture produced from organic matter under anaerobic conditions through the action of a microbial consortium in anaerobic digestion (AD). As a widely used renewable energy source, biogas plays a crucial role in waste-to-energy utilization, reducing greenhouse gas emissions, and providing clean energy.

The feedstock sources for biogas are extremely diverse. A wide range of biodegradable organic wastes can be used for biogas production, such as agricultural residues, municipal waste, industrial organic by-products, and energy crops [57–59].

The production of biogas primarily relies on AD, which is carried out in sealed digesters or biogas reactors. AD is a multistage biochemical process in which complex organic matter is decomposed into methane-rich gas by a series of microbial activities. The process involves four interrelated stages [60,61]. The first is hydrolysis, during which proteins, lipids, and carbohydrates are broken down into amino acids, long-chain fatty acids, and monosaccharides by extracellular enzymes. This is followed by acidogenesis (fermentation), where hydrolysis products are further degraded into volatile fatty acids, such as acetic, butyric, and propionic acids, accompanied by the formation of hydrogen and carbon dioxide. The third stage is acetogenesis (anaerobic oxidation), in which propionic acid, butyric acid, and alcohols are oxidized to generate acetic acid, hydrogen, and carbon dioxide. Finally, methanogenesis occurs, which can be further divided into acetoclastic methanogenesis and hydrogenotrophic methanogenesis. In acetoclastic methanogenesis, acetic acid is cleaved into methane and carbon dioxide, and under mesophilic conditions, this is the dominant pathway, accounting for approximately 70% of total methane production. Hydrogenotrophic methanogenesis utilizes hydrogen and carbon dioxide to form methane, contributing roughly 30%.

The AD process is highly sensitive to operational parameters such as temperature, pH, organic loading rate, and mixing, all of which directly affect microbial activity, reaction rates, and biogas yield [62].

Pretreatment methods for biomass are typically categorized into three main groups: physical, chemical, and biological methods. Physical methods primarily involve reducing particle size and increasing surface area through techniques like grinding, milling, and extrusion [63,64]. Chemical methods utilize acids, bases, or solvents to break down the complex structure of biomass, with common examples including acid hydrolysis and alkaline treatment [65]. Biological methods rely on microorganisms or enzymes to degrade lignin and hemicellulose [66].

However, to overcome the limitations and enhance the efficiency of single-stage processes, some studies have employed combined methods that integrate two or more basic techniques [67]. For instance, examples include the thermal–alkali hybrid pretreatment technique, which combines thermal and chemical methods [68]; biomechanical pretreatment, which integrates biological and mechanical approaches [69]; and chemo-sonication pretreatment, which leverages the benefits of both chemical and ultrasonic pretreatment processes [70].

The main components of biogas are methane (CH_4) and carbon dioxide (CO_2), with trace amounts of impurities.

During the combustion of biogas, these impurities can lead to the formation of sulfur oxides (SO_x) and particulate deposits. SO_x, when combined with water, form sulfurous acid, which causes severe corrosion and poisoning to engine liners, pistons, exhaust valves, and aftertreatment systems (e.g., catalysts) [71]. Particulate deposits accumulate on equipment surfaces, leading to operational failures and mechanical damage [72]. Therefore, the removal of these impurities is essential before utilizing biogas.

3. Application of Biomass Gases in Diesel Engines

DF diesel engine systems exhibit excellent fuel flexibility, economic benefits, and relatively low emissions, providing significant advantages in replacing conventional diesel power systems [73]. From an environmental perspective, DF engines demonstrate significant potential for emission reduction.

Numerous studies have shown that DF operation with gaseous fuels can substantially reduce pollutant emissions, thus contributing to compliance with increasingly stringent emission regulations [74]. Specifically, SO_x emissions are often eliminated entirely because

biomass-derived gases inherently contain little to no sulfur [75]. Furthermore, the partial substitution of fossil diesel by carbon-neutral biomass fuels contributes significantly to the reduction in net CO_2 emissions [76]. While the effect on NO_x is complex and dependent on operating conditions, DF mode generally offers opportunities for optimization [77–79].

This is primarily because gaseous fuels contain no sulfur and have a lower carbon-to-hydrogen ratio, leading to more complete combustion. In addition, the introduction of gaseous fuels improves mixture formation quality, which helps suppress particulate matter (PM) generation. However, it should also be noted that under certain operating conditions, due to delayed combustion phasing or mixture inhomogeneity, emissions of unburned UHC or CO may slightly increase.

In conventional DF systems, gaseous fuel is typically mixed with air in the intake manifold and inducted into the cylinder. Near the end of the compression stroke, a small amount of diesel is injected as a pilot fuel. The injected diesel auto-ignites rapidly, forming a hot ignition kernel that initiates combustion of the surrounding premixed gaseous-air mixture. This combustion process retains the stable and reliable features of compression ignition while introducing characteristics of premixed flame propagation. The combustion process in DF diesel engines can be divided into five stages: ignition delay, premixed combustion, main-fuel ignition delay, uncontrolled combustion of the main fuel, and post-combustion, as shown in Figure 1 [11].

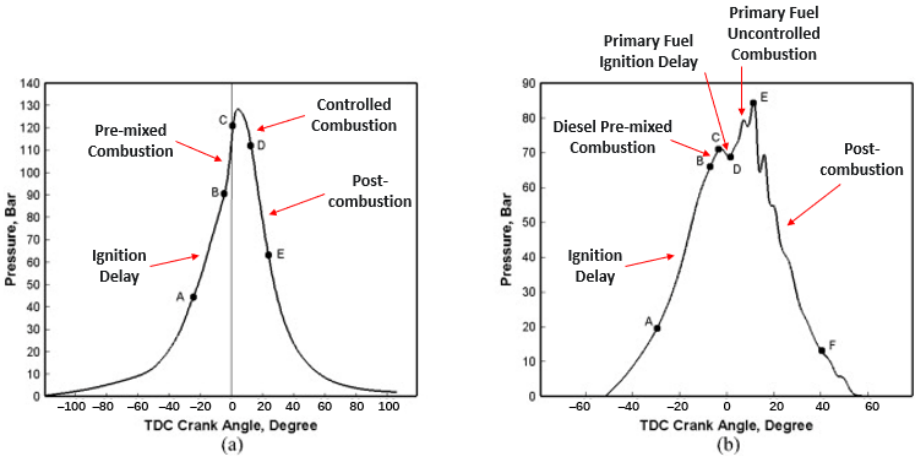


Figure 1. Comparison of combustion stages and heat release rate profiles between (**a**) conventional diesel engine and (**b**) dual-fuel diesel engine (adapted and replotted based on the schematic presented in Ref. [11]).

When manifold injection is employed, unburned high-temperature gases may ignite residual fuel-air mixtures in the intake manifold, resulting in backfire. Such events can damage engine components and even affect the fuel supply system, creating serious safety hazards. Therefore, flame arrestors and other safety measures must be installed in fuel supply lines to prevent flame flashback [80].

Furthermore, the gas–diesel DF fueling strategy can also be combined with various low-temperature combustion modes, such as premixed partially premixed compression ignition (PPCI), reactivity controlled compression ignition (RCCI), and homogeneous charge compression ignition (HCCI), to further control exhaust emissions.

In PPCI, fuel is injected earlier, allowing part of the fuel to premix with air before ignition. Subsequently, auto-ignition occurs near the end of compression under high-temperature and high-pressure conditions [81]. The core principle of PPCI is the combination of premixing, compression ignition, and low flame temperature, enabling ICEs to

achieve efficient and clean combustion while significantly reducing NO_x and PM emissions [82].

HCCI is an advanced combustion mode that combines the advantages of both gasoline and diesel engines. In HCCI, fuel and air are thoroughly premixed before entering the cylinder or within the intake port. Compared with PPCI, the fuel–air mixture in HCCI is nearly homogeneous, and auto-ignition occurs during compression due to increased in-cylinder temperature and pressure. Since the combustion process lacks distinct flame propagation and diffusion flames, HCCI features low combustion temperature and ultra-low NO_x and PM emissions [83]. However, challenges remain for its application in diesel engines, particularly the difficulty of precisely controlling ignition timing and the limited load range. Typically, HCCI is more suitable for medium to low loads and is highly sensitive to fuel chemical stability and composition [84].

RCCI is a recently proposed high-efficiency, low-emission combustion strategy. Its core concept is to use both low-reactivity fuel and high-reactivity fuel to form a stratified reactivity distribution in the cylinder, thereby enabling precise control of combustion timing and heat release rates [85]. The low-reactivity fuel is usually premixed with air via the intake manifold, while the high-reactivity fuel is injected during the late compression stroke in a controlled manner to initiate ignition and regulate the overall combustion process [86]. Compared with conventional DF combustion, RCCI can significantly reduce knocking tendency, expand the load operating range, and effectively suppress NO_x and PM emissions while maintaining high efficiency.

4. Influence of Biomass Gases on Engine Performance

4.1. Influence of Biosyngas on Engine Performance

In terms of diesel substitution rates, literature reviews have indicated that, depending on operating conditions, the maximum substitution rate of syngas for diesel can reach 45–90% [87]. However, when diesel substitution exceeds a certain level, engine thermal efficiency generally declines as the proportion of gaseous fuel increases. Moreover, problems such as knocking and unstable combustion further restrict the maximum substitution rate.

Producer gas (PG), due to its lower calorific value compared with biosyngas, faces additional limitations on maximum substitution. For example, Carlo Caligiuri et al. [88] tested a micro-CHP system based on a compression-ignition diesel engine under DF operation with diesel and forestry biomass-derived PG. In this system, the maximum diesel substitution rate was 50%. At low, medium, and high loads, electrical efficiency decreased by approximately 40%, 20%, and 10%, respectively, while thermal efficiency decreased by an average of about 28% across all tested loads [88]. Table 2 presents the effects of biosyngas on various engine performance parameters reported in multiple studies.

In diesel–biosyngas DF mode, notable changes in combustion characteristics are manifested as slower and more homogeneous combustion, resulting in reduced heat release rates and lower in-cylinder pressures [89,90]. This phenomenon is mainly attributed to the physicochemical properties of biosyngas and its effects on combustion mechanisms. First, biosyngas generally contains higher proportions of non-combustible components (e.g., CO_2 and N_2), which dilute the overall energy density of the in-cylinder mixture, naturally slowing down combustion rates. Second, biosyngas has a very low cetane number and poor auto-ignition quality, prolonging ignition delay and increasing the share of the premixed combustion phase, while reducing combustion intensity [91]. In addition, when gaseous biosyngas–air mixtures are ignited by diesel, their flame propagation speed is usually lower than that of diesel spray diffusion flames, leading to a smoother energy release process.

Table 2. Comparison of performance parameters between dual-fuel mode with biosyngas/producer gas and conventional diesel mode.

Fuels	Engine Type	Operating Conditions	Combustion	Performance	Emission	Ref.
PG-diesel	Multi-fuel VCR (variable compression ratio) engine	Load: 90% Speed: 1500 rpm IT: 23° BTDC	-	BTE: ↓ (Max: 26%) BSEC: ↓ (Min: 14.7 MJ/kWh)	CO: ↑(Min: 0.07 vol.%) HC: ↑(M: 28.8 ppm) NO_x: ↓ Smoke: ↓ (Min: 17.5%)	[92]
PG-H_2-diesel	4-stroke, 1-cylinder, direct injection diesel engine	Load: 90% Speed: 1500 rpm IT: 27° BTDC	-	(at 5% EGR vs. 10% EGR)BTE: ↓2.1%	(at 5% EGR vs. 10% EGR) HC: ↓8.01% CO: ↓14.5% NO_x: ↑32.2% Smoke: ↓10.2%	[93]
PG-biodiesel-diethyl ether	4-stroke, 2-cylinder diesel engine	Power: 14 hp Speed: 1500 rpm	CP: ↓ HRR: ↓ MCT: ↓	BTE: ↓5.9%	-	[90]
Syngas–biodiesel	4-cylinder diesel engine	-	-	-	CO: ↑ HC: ↑ NO_x: ↓ Smoke: ↑	[94]
PG-diesel	4-stroke, 1-cylinder, direct injection diesel engine	BMEP: 0–700 kN/m^2 Speed: 1500 rpm	-	BTE: ↓ BSEC: ↑	CO: ↑ CO_2: ↑ Smoke: ↓	[95]
PG-diesel	4-stroke, 1-cylinder, VCR diesel engine	Load: 19.6 N–117.6 N Compression ratio: 18	-	BTE: ↓ (Min: 2.76%; Max: 23.34%) BSEC: ↓	CO: ↑(Max: 0.0253 vol.%) HC: ↑ NO_x: ↓69.5% (Max: 42 ppm)	[96]
PG-diesel	Direct injection diesel engine	Load: 75% Speed: 1500 rpm	-	BTE: ↑40%	CO: ↓ HC: ↓ NO_x: ↑ Smoke: ↓	[97]

↑ indicates that the displayed fuel combination performs better in the corresponding parameter compared to pure diesel operation under the specified conditions; ↓ indicates the opposite trend.

This combination of effects—a prolonged ignition delay followed by a slower flame propagation—fundamentally alters the combustion phasing and extends the overall combustion duration. The initial pilot diesel ignition triggers the combustion of the premixed syngas–air charge, but the subsequent energy release is stretched over a longer period compared to the rapid diffusion burning of pure diesel spray. Consequently, the combined effect typically leads to a lower peak in-cylinder pressure and a broader, smoother heat release curve. The specific H_2/CO ratio in the syngas is a critical factor here; higher hydrogen content can partially counteract these trends by enhancing the laminar flame speed, thereby shortening the combustion duration and improving combustion stability.

Brake thermal efficiency (BTE), a key indicator of the conversion of thermal energy into mechanical work, is often reduced under this smoother combustion regime. Although such combustion is beneficial for lowering NO_x emissions and reducing engine thermal load, it usually comes at the cost of decreased BTE. Mohit Sharma et al. [98] investigated

the performance and emission characteristics of a variable compression ratio diesel engine operating in DF mode with PG obtained from walnut shell gasification. The maximum BTE values were 25.63% and 21.61% under diesel and DF operation, respectively. In another study, Mohit Sharma et al. [99] examined PG derived from pistachio shell gasification in a diesel engine. Under pure diesel and DF operation, the maximum BTE values were 25.71% and 23.81%, respectively, while the maximum brake specific fuel consumption (BSFC) values were 0.37 kg/kW·h and 0.837 kg/kW·h, respectively. The low calorific value of PG necessitates increased fuel flow rates to maintain equivalent power output, resulting in higher mass or energy consumption [100]. Under certain operating conditions, DF operation may also cause incomplete combustion due to air deficiency, thereby reducing power output [96]. Some researchers argue that the reduction in brake power is not mainly due to the combustion characteristics of PG itself, but rather the additional energy losses introduced by modifications to the fuel injection system required for gaseous fuel adaptation [101].

To overcome these issues, several strategies have been proposed, including intake boosting, optimization of injection strategies, and adjustment of syngas composition. Increasing intake pressure allows greater fuel delivery, thereby significantly extending the high-load operating range of the engine. The composition of syngas varies considerably depending on the feedstock used, which affects its performance in diesel engines, particularly the ratio of H_2 to CO [102]. Higher H_2 content enhances combustion speed and ignition characteristics, whereas increased CO content may cause unstable combustion and slower flame propagation [103].

4.2. Influence of Biogas on Engine Performance

Using biogas as the primary fuel in DF diesel engine systems can achieve diesel savings of more than 80% [11]. Himsar [104] tested a small CI engine with a rated power of 4.41 kW operating under DF (diesel–biogas) mode, where the maximum diesel substitution rate reached 87.5%. Saket et al. [105] tested biogas with three different CH_4 concentrations in DF mode, and under low load conditions, the diesel substitution rate reached 80–90%.

Table 3 presents the effects of biogas on various engine performance parameters reported in multiple studies. Increasing the share of biogas generally leads to a reduction in combustion stability, which is particularly evident under low loads, although it typically remains within acceptable stability limits [106]. When the biogas–air homogeneous mixture is ignited by diesel, a larger proportion of fuel burns rapidly during the premixed combustion phase, making the combustion process closer to constant volume combustion and resulting in higher peak cylinder pressure. However, due to the dilution effect of CO_2, the combustion rate is slowed, which may cause the peak heat release rate (HRR) in DF mode to be lower than in pure diesel operation. The high specific heat capacity of CO_2 significantly increases the ignition delay by lowering the temperature and pressure trajectory during compression. Upon ignition, the rapid combustion of the well-premixed methane–air charge can lead to a sharper initial pressure rise. However, the presence of CO_2 simultaneously acts as a chemical and thermal suppressant, slowing the subsequent flame propagation and thus reducing the peak HRR and extending the combustion duration. This complex interplay between methane's high reactivity and CO_2's inhibition results in a highly variable combustion process that is sensitive to the biogas composition (CH_4/CO_2 ratio), engine load, and injection timing. This limitation can be mitigated through optimization of injection strategies [107]. For instance, Prasant et al. [108] investigated HRR at different injection timings and found that advancing the fuel injection timing to 25° reduced the HRR drop from 9.59% to 1.88% compared with pure diesel mode. Furthermore, increasing the biogas energy fraction can enhance peak cylinder pressure and HRR [109].

Kumarasubramanian et al. [107] reported that biogas enriched with ammonia could further improve HRR in diesel engines.

A higher biogas fraction in the fuel mixture reduces the efficiency of converting energy into mechanical work, resulting in lower BTE. This occurs because methane, the main component of biogas, has lower combustion efficiency compared with other fuel components in the mixture [110]. At lower enrichment levels, the difference in efficiency is minor, but as the biogas energy fraction increases, the combustion process slows down significantly, leading to a marked reduction in efficiency. At the same time, introducing biogas into the fuel mixture can result in higher fuel consumption.

To address these challenges, researchers have proposed optimizing DF operating parameters such as fuel injection parameters, compression ratio (CR), and load. Naseem et al. [111] achieved a maximum BTE of about 31.2–4.5% higher than pure diesel operation at full load by adjusting fuel injection parameters and CR. Avadhoot et al. [14] employed response surface methodology (RSM) to optimize CR, injection timing, and load, maintaining acceptable BTE levels while significantly improving exhaust emissions. Amar et al. [112] also applied RSM for multi-response optimization of engine load, CR, and the biogas–fuel ratio, successfully controlling BSFC at 0.46 kg/kWh while simultaneously reducing CO, HC, and NO_x emissions.

Table 3. Comparison of performance parameters between dual-fuel mode with biogas and conventional diesel mode.

Fuel	Engine Type	Operating Conditions	Combustion	Performance	Emission	Ref.
Biogas–diesel	4-stroke, 1-cylinder diesel engine	Biogas Flow Rate: 8–16 L/min Torque: 5–15 N-m Intake Temperature: 35–80 °C	-	BSFC: ↑ BTE: ↓	HC: ↓ Smoke: ↓ NO_x: ↑	[113]
Biogas–diesel	4-stroke, 1-cylinder, direct injection diesel engine	Load: 100% Speed: 1500 rpm	-	BSFC: ↑36% BTE: ↓6.2%	CO: ↑17% HC: ↑30% CO_2: ↓42% NO_x: ↓39% Smoke: ↓49%	[114]
Biogas–diesel	4-stroke, 1-cylinder, direct injection, VCR diesel engine	Load: 20–100% Speed: 1500 rpm IT: 23–32° BTDC CR: 17–18	CP: ↓ HRR: ↓	BSFC: ↑(Optimized Value: 1.98 kg/h) BTE: ↓(Optimized Value: 19.38%)	HC: ↑(Optimized Value: 0.314 g/kWh) CO: ↑(Optimized Value: 0.694 g/kWh) CO_2: ↓(Optimized Value: 276.34 g/kWh) NO_x: ↓(Optimized Value: 0.381 g/kWh)	[115]
Biogas–diesel	4-stroke, 1-cylinder diesel engine	Load: 20–100% Speed: 1500 rpm IT: 23° BTDC CR: 16	-	BTE: ↓30.0%	CO: ↓ HC: ↑ NO_x: ↓	[116]

Table 3. *Cont.*

Fuel	Engine Type	Operating Conditions	Combustion	Performance	Emission	Ref.
Biogas–diesel–MWCNT	4-stroke, 3-cylinder, direct injection diesel engine	Load: 0–100% Speed: 1500 rpm	CP: ↑	BSFC: ↑ BTE: ↓8.0%	CO: ↑ HC: ↑ NO_x: ↓23.0%	[117]
HEB-diesel	4-stroke, 1-cylinder, direct injection diesel engine	Load: 20–100% Speed: 1500 rpm IT: 13° BTDC	-	BSFC: ↓	CO: ↑ HC: ↑ NO_x: ↓ Smoke: ↓	[118]
HEB-diesel	4-stroke, 1-cylinder, CRDI diesel engine	Load: 80% Speed: 1800 rpm IT: 20.84° BTDC	-	BSFC: ↓13.6% BTE: ↑10.5%	HC: ↓ Smoke: ↓ NO_x: ↑	[119]
HEB-diesel	4-stroke, 1-cylinder, VCR diesel engine	BMEP: 3.5–1500 bar CR = 16–18	CP: ↑ HRR: ↓	BTE: ↑12.8%	CO: ↓ HC: ↓ NO_x: ↑ Smoke: ↓	[120]

↑ indicates that the displayed fuel combination performs better in the corresponding parameter compared to pure diesel operation under the specified conditions; ↓ indicates the opposite trend.

5. Influence of Biomass Gases on Exhaust Emissions

5.1. Influence of Biosyngas on Exhaust Emissions

As shown in Table 2, compared to conventional diesel combustion, syngas combustion generally reduces NO and soot emissions. This reduction is primarily attributed to the dilution and cooling effects of CO_2 and N_2 within the gaseous mixture. Simultaneously, the elevated levels of CO and HC observed in most studies indicate incomplete oxidation at lower combustion temperatures [92]. The extent of emission variations is also closely related to the gas composition and operating load. Increasing the hydrogen content in the syngas often improves oxidation efficiency, leading to a decrease in CO and HC emissions [93]. However, NO_x emissions may increase significantly due to the resulting higher flame temperature. These trends highlight the importance of balancing different emissions. These general trends are consistently supported by extensive experimental studies in the literature.

Compared with conventional diesel operation, DF mode results in significantly higher emissions of CO and HC [121–123]. Under certain operating conditions (e.g., low load), insufficient combustion temperature may cause incomplete combustion; in addition, the CO present in syngas directly contributes to exhaust emissions.

The relative hydrogen content in syngas plays a critical role in mitigating the negative impact on CO and UHC emissions [124]. CO_2 in biosyngas provides dilution and cooling effects, lowering in-cylinder combustion temperature and thereby suppressing the formation of thermal NO_x. Narankhuu et al. [125] reported that, under a fixed LHV, increasing H_2 content while reducing CO content effectively decreased CO emissions while maintaining very low NOx levels. Zhen et al. [126] optimized operating parameters such as fuel supply, syngas composition, and intake conditions in a syngas/diesel RCCI engine under a wide load range, and demonstrated that NO_x emissions could be kept at very low levels.

Jatinderpal Singh et al. [127] investigated the operation of a DF compression ignition engine running on syngas–diesel dual fuel. At maximum load conditions, diesel consumption decreased by up to 44.44%, with indicated power slightly reduced by 3.49%. In

addition to fuel savings, NO_x emissions were reduced by up to 76.74% compared with standard diesel operation.

Rabello et al. [128] summarized the influence of syngas composition on engine operation and exhaust emissions, showing that increasing CO fraction effectively reduced NO_x emissions; however, excessive CO_2 could reduce combustion efficiency.

5.2. Influence of Biogas on Exhaust Emissions

As shown in Table 3, the emission pattern of biogas–diesel dual-fuel systems is more complex. Due to the slower flame speed of methane and the quenching effect of CO_2, CO and HC emissions typically increase as the biogas substitution ratio rises [115]. Conversely, NO_x and soot emissions consistently decrease due to lower combustion temperatures and improved mixture homogeneity [114]. The CO_2 concentration in biogas acts both as a diluent and a temperature regulator. It promotes soot oxidation while simultaneously suppressing NO_x formation. When biogas is used in combination with metal-based additives, combustion stability improves, which consequently reduces HC and CO emissions, though sometimes leading to a slight increase in NO_x emissions at high loads [117]. These findings confirm that emission outcomes are closely related to both biogas composition and engine parameters.

Emissions of CO and hydrocarbons (HCs) tend to increase [129–131]. This is mainly due to the slow combustion rate of biogas, which easily causes after-burning (incomplete combustion), while the dilution effect of CO_2 may lead to partial quenching or increased unburned regions, particularly under low-load conditions. Mehmet [132] studied exhaust characteristics when introducing biogas and acetylene-enriched biogas. Compared with pure diesel mode, UHC increased by 45.5% and 57.6%, respectively, while CO emissions increased by 175.82% and 373.4%, respectively.

Life-cycle CO_2 emissions are significantly reduced. Although the total direct CO_2 emissions from the engine remain similar, the carbon in biogas originates from biomass (e.g., organic waste), which is carbon-neutral. The CO_2 released during combustion is reabsorbed during the growth of the next biomass generation [133]. Therefore, the use of biogas reduces reliance on fossil fuels and lowers the net carbon emissions of the energy system [134].

Emissions of NO_x are usually reduced significantly [135]. On the one hand, the CO_2 content in biogas decreases the combustion temperature. On the other hand, once the biogas–air mixture is ignited by the pilot diesel, combustion becomes more homogeneous. This homogenized combustion avoids localized high-temperature zones typical of conventional diesel engines, producing a more uniform temperature distribution and thereby suppressing NOx formation in hot spots [89,132].

Particulate matter (PM) and smoke emissions generally improved, showing noticeable reductions. This is because biogas forms a homogeneous premixed mixture with air, leading to more complete combustion and fewer fuel-rich zones, which suppresses soot formation [14]. Saket et al. [109] compared smoke emissions in DF mode using biogas, compressed natural gas, and hydrogen as primary fuels. Results indicated that biogas consistently produced the lowest smoke levels across the entire operating range.

6. Discussion and Scope for Future Prospects

This review synthesizes the complex interactions between biomass gas properties and dual-fuel engine performance. The primary influence stems from the variability in gas composition—notably the H_2/CO ratio in syngas and the CH_4/CO_2 ratio in biogas—which directly governs ignition delay, combustion stability, and emission formation. The dilution effect of CO_2 and N_2 effectively lowers the combustion temperature, serving as

the principal mechanism for the significant suppression of NO_x emissions observed across most studies. However, this same mechanism slows the combustion rate and can lead to incomplete combustion, particularly at low loads, explaining the frequently reported increases in CO and unburned HC emissions.

Despite extensive research, inconsistencies remain regarding the impact of composition on combustion efficiency. A key point of divergence lies in the trade-off between emission reduction and brake thermal efficiency, which is highly sensitive to hydrogen enrichment levels and operational load. Furthermore, the scarcity of long-term durability data and validation under real-world, transient conditions presents a major barrier to industrial adoption. Future work must, therefore, extend beyond combustion optimization to address the system-level integration of upstream gas purification and downstream carbon capture technologies, forming a complete and viable energy pathway.

Future research can focus on the following directions:

The variability in biomass gas composition represents a major barrier to stable and efficient engine operation. Future work should focus on developing efficient and low-cost purification technologies, as well as online monitoring and feedback control strategies for gas composition, to provide engines with relatively stable and controllable fuel quality.

Given the characteristics of biomass gases, more refined combustion system matching studies are required. This includes optimization of injection strategies, swirl ratio, CR, and EGR rate. In addition, intelligent control systems based on artificial intelligence and model predictive control should be developed to adjust operating parameters in real time, adapting to variations in gas composition and load to ensure high-efficiency, clean combustion across the full operating range.

Further investigation is warranted on the application of biomass gases in advanced combustion modes, including RCCI. Research should investigate the synergistic effects between biomass gases and fuels of varying reactivity to achieve precise control of the combustion phasing, thereby overcoming NO_x–soot emission trade-offs across a wider load range.

From an energy system perspective, the entire chain of biomass gas production, purification, and engine utilization should be analyzed for technical and economic feasibility, assessing true carbon reduction potential. Integration of biomass gasification and anaerobic digestion with power generation, heating, and carbon capture technologies can be facilitated via modular and distributed energy system design.

7. Novelty and Limitations

7.1. Novelty of This Review

This review contributes several novel aspects to the existing literature on biomass gases in dual-fuel engines:

Systematic Comparative Analysis: It provides a concurrent and systematic comparison of two primary biomass-derived gases—biosyngas and biogas—highlighting their distinct effects on engine combustion, performance, and emission characteristics, which are often treated separately in other works.

Integration with Advanced Combustion Modes: It moves beyond conventional dual-fuel operation by comprehensively integrating and analyzing the potential of combining these gases with advanced low-temperature combustion modes, such as reactivity-controlled compression ignition (RCCI) and premixed partially controlled ignition (PPCI), to overcome the efficiency–emission trade-off.

Holistic Perspective: It adopts a unique, whole-chain perspective that critically links upstream factors like gas production methods and composition variability with down-

stream engine adaptation strategies and system-level optimization, offering a more cohesive understanding of the technology's viability.

7.2. Limitations of This Review

Despite its comprehensive scope, this study is subject to certain limitations:

Data Heterogeneity: The significant variability in biomass gas compositions, engine configurations, and operating conditions across the cited literature makes direct quantitative comparisons challenging and limits the generalizability of specific numerical findings.

Techno-Economic Scope: While critical for commercialization, a detailed techno-economic analysis and a full life-cycle assessment fall outside the primary technical focus of this review, though they are acknowledged as vital areas for future work.

8. Conclusions

This paper systematically reviewed the preparation methods, physicochemical properties, and applications of two main types of biomass gas—biosyngas and biogas—in dual-fuel diesel engines.

Firstly, regarding gas characteristics, biosyngas is primarily obtained through biomass gasification technology. Its composition is variable, with a wide range of heating values and impurities, necessitating purification before use. Biogas, derived from the anaerobic digestion of organic waste, is mainly composed of methane and carbon dioxide, with its yield and quality significantly influenced by feedstock and process parameters.

In terms of application, dual-fuel technology is a key pathway for efficiently utilizing biomass gases. This approach, which involves pre-mixing the gaseous fuel in the intake manifold and using a small amount of diesel for pilot ignition, enables flexible fuel substitution. It can also be combined with advanced low-temperature combustion modes such as PPCI, HCCI, and RCCI to optimize combustion and control emissions. Studies indicate that the introduction of biomass gases generally leads to a milder combustion process, characterized by reduced in-cylinder peak pressure and heat release rate, as well as a potentially prolonged ignition delay. This is primarily attributed to the dilution effect of gaseous fuel, its low cetane number, and different flame propagation modes. Economically, the dual-fuel mode often leads to a decrease in BTE and an increase in BSFC. The main reasons for this include the lower calorific value of gaseous fuel, slower combustion speed, and parameter adjustments made for high substitution rates. However, these aspects can be improved through optimization of parameters such as injection timing and compression ratio.

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Abbreviations

AD	Anaerobic Digestion
BMEP	Brake Mean Effective Pressure
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
CH_4	Methane
CI	Compression Ignition
CP	Compression Pressure
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CR	Compression Ratio
DF	Dual Fuel
EGR	Exhaust Gas Recirculation
HRR	Heat Release Rate
HCCI	Homogeneous Charge Compression Ignition
HHV	High Heating Value
ICE	Internal Combustion Engine
LHV	Low Heating Value
LTC	Low-Temperature Combustion
MCT	Mean Combustion Temperature
NO_x	Nitrogen Oxides
PPCI	Premixed Partially Controlled Ignition
PG	Producer Gas
RSM	Response Surface Methodology
RCCI	Reactivity Controlled Compression Ignition
VCR	Variable Compression Ratio
UHCs	Unburned Hydrocarbons
PM	Particulate Matter
SO_x	Sulfur Oxides
H_2	Hydrogen

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