

# Comparative Emissions of Syngas, Biogas, and LPG in Spark-Ignition Engines for Sustainable Power Generation

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Received: 5 August 2025 | Revised: 28 August 2025 | Accepted: 9 September 2025

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## ABSTRACT

This study provides a comparative analysis of the performance and emissions of internal combustion engines powered by different alternative fuels: syngas from agricultural and woody biomass, biogas, and Liquefied Petroleum Gas (LPG). Syngas was generated using a reduction gasifier and was utilized in a 10 kW Spark-Ignition Engine (SIE), whereas biogas and LPG were tested in a 1 kW SIE. The results from the smaller engine were mathematically adjusted to match the 10 kW SIE for a consistent comparison. The engine performance was assessed based on Brake Thermal Efficiency (BTE) and Specific Fuel Consumption (SFC). Additionally, exhaust emission levels of carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>), and unburned hydrocarbons (HCs) were measured and compared. Syngas produced the highest CO<sub>2</sub> emissions, particularly from wood-derived biomass, with values reaching up to 3.7821 kg/kWh. In contrast, LPG and biogas emitted significantly lower CO<sub>2</sub> levels. Syngas also showed higher CO and HC emissions, reflecting incomplete combustion and fuel inefficiency, while LPG and biogas exhibited lower CO and minimal HC emissions. The NO<sub>x</sub> emissions were notably higher when syngas fuel was used due to elevated flame temperatures, while LPG and biogas demonstrated a better combustion efficiency with lower NO<sub>x</sub> levels. Overall, this study highlights the potential of biomass-derived gaseous fuels for low-emission and sustainable energy production. While LPG offers stable combustion, syngas and biogas present promising results, particularly as waste-derived fuels, contributing to decentralized and eco-friendly energy generation.

**Keywords-syngas; biogas; biomass gasification; internal combustion engine; engine performance; LPG**

## I. INTRODUCTION

A viable synergy can be achieved through a scheme that utilizes the gasification process to produce syngas from agricultural and wood waste, which can then be used as fuel to power internal combustion engines. This process usually involves heating biomass, such as agricultural residues or wood waste, in a low-oxygen atmosphere to form a gaseous mixture largely containing CO, H<sub>2</sub>, and CH<sub>4</sub>. In addition, this process solves environmental problems related to the waste management while offering a renewable source of energy that can help sustain the agricultural activities without contributing to the carbon emissions [1, 2]. Specifically, producer gas can be used in both diesel and gasoline engines. However, problems, such as tar formation and engine de-rating, continue to arise [3].

New developments in gasification have pointed to the possibility of independent power production, which is more

suitable for rural centers, especially if fueled by agricultural waste. Decentralized energy systems enable the organization of energy production on a small scale for a specific area, avoiding the dependency on centralized grids and fossil fuels, while promoting localized sustainability [4, 5]. From an environmental perspective, the gasification minimizes the methane emissions that typically arise from the uncontrolled decomposition of agricultural waste, thus reducing the carbon footprint of the waste management practices [1]. Downdraft gasifiers are particularly effective for small-scale energy production because of their ability to generate cleaner syngas with lower tar content. This makes them ideal for rural and decentralized energy systems [6]. The syngas generated in such systems can power spark-ignition engines in either single- or dual-fuel modes, offering a pathway to replace fossil-based fuels in developing areas.

To further support the viability of this approach, multiple studies have experimentally evaluated the biomass-derived



The exhaust gas analyzer used in this study was calibrated to measure the emissions with high precision, ensuring accurate readings for CO<sub>2</sub>, CO, NO<sub>x</sub>, HCs, and CH<sub>4</sub>. The conversion of the volume percentage emissions to kg/kWh was based on the ideal gas law principles and specific equipment calibration, ensuring accurate and reliable comparisons.

The incomplete combustion was quantitatively assessed by the elevated concentrations of CO and HCs in the exhaust. Although a precise measure of the combustion efficiency was not available owing to equipment limitations, future studies will incorporate advanced metrics, including the air-fuel ratio and detailed combustion efficiency, to provide a clearer picture of the fuel performance.

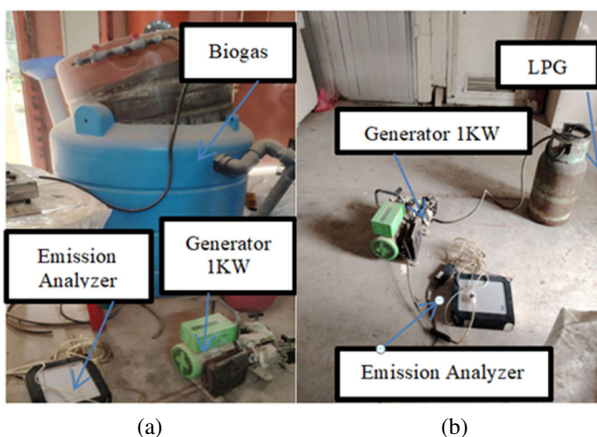


Fig. 2. (a) 1 kW generator during biogas testing under laboratory conditions. (b) 1 kW generator operating using LPG.

### III. RESULTS AND DISCUSSION

The performance of the 10 kW SIE was analyzed using three gaseous fuels: syngas produced from biomass gasification, biogas, and LPG. The emissions of CO<sub>2</sub>, CO, NO<sub>x</sub>, CH<sub>4</sub>, and unburned HCs were measured to evaluate the environmental impact and combustion efficiency of each fuel.

#### A. Generator Emissions Using Syngas

The exhaust gases emitted from the generator were measured after operation using syngas produced from the gasification of four fuel types: 100% corn husks, 100% wood, 30% wood + 70% corn, and 70% wood + 30% corn. The measurements were conducted using an exhaust gas analyzer. Table I depicts the volume percentages of the gas emissions, which were converted to kilograms per kilowatt-hour (kg/kWh) to assess the actual environmental impact of each fuel type.

CO<sub>2</sub> was the largest component of the exhaust, with the highest percentage produced using pure wood fuel (97.73%), whereas CO<sub>2</sub> decreased slightly when using the 30% wood + 70% corn mixture (97.21%). In terms of the emission mass, the highest emission of CO<sub>2</sub> in kg/kWh was achieved using the 70% wood + 30% corn mixture (3.78 kg/kWh). This can be attributed to the lower heating value of the gas produced from this mixture, which requires a larger amount of gas to generate the same amount of energy.

The highest percentage of CO was recorded using the 30% wood + 70% corn mixture (1.82%), followed by pure corn husks (1.77%), reflecting a higher partial combustion efficiency when corn was used as the primary source. When converting the values to kg/kWh, the highest CO emissions were also recorded for the 70% wood + 30% corn mixture (0.037 kg/kWh).

The nitrogen oxide levels increased in all cases, with the highest percentage recorded using a 30% wood + 70% corn mixture (0.47%). This increase may be due to the higher local temperatures within the combustion chamber. The highest mass value of NO<sub>x</sub> was recorded for the 70% wood + 30% corn mixture (0.017 kg/kWh).

CH<sub>4</sub> and unburned HCs were found in the highest percentage concentrations using the 30% wood + 70% corn mixture, indicating incomplete combustion of the syngas in this case, despite the high energy content of the syngas. Figure 3 portrays the gas emissions for the different fuel types.

TABLE I. EMISSIONS GENERATED FROM BURNING SYNGAS IN A 10 KW SIE

Feedstock	CO <sub>2</sub> (kg/kWh)	CO (kg/kWh)	NO <sub>x</sub> (kg/kWh)	CH <sub>4</sub> (kg/kWh)	HC (kg/kWh)
70% wood + 30% corn	3.78213	0.0373093	0.0173032	0.00351854	0.00235551
100% wood	2.77559	0.0243438	0.0120742	0.00206002	0.00155148
100% corn cobs	2.39562	0.0252367	0.0112321	0.00241067	0.00156901
30% wood + 70% corn	2.45255	0.0265935	0.0122956	0.00256199	0.00176108

#### Gas Emission Comparison

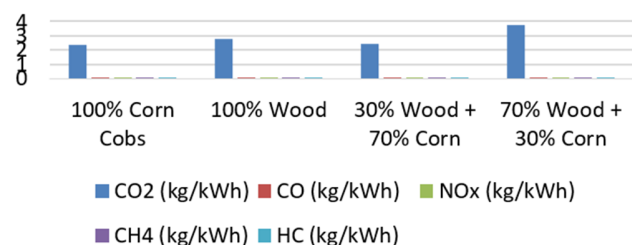


Fig. 3. Emissions from SIE fueled with syngas produced by gasification.

#### B. Generator Emissions Using Biogas

The gases emitted from a 1 kW internal combustion engine running on biogas were analyzed using a portable emission meter. The results are presented in Table II. CO<sub>2</sub> recorded the highest concentration among the pollutants due to the relatively complete combustion of the biogas, indicating relatively good combustion efficiency.

The presence of CO at 0.18 vol % reflects a partially incomplete combustion, which is expected in a small generator running on heterogeneous biofuel.

The concentration of unburned HCs was 168 ppm, indicating the presence of organic compounds not fully decomposed, which is expected with biogas due to its complex composition.

The concentration of NO<sub>x</sub> was 250 ppm. This value reflects the average level of NO<sub>x</sub> emissions that may result from combustion at relatively moderate temperatures. The emissions from biogas are illustrated in Figure 4.

TABLE II. EMISSIONS GENERATED FROM BURNING BIOGAS IN A 1 KW SIE

Gas	Value	Unit	kg/kWh	kg/10kWh
CO <sub>2</sub>	10.6	% vol	0.001874	0.018744
CO	0.18	% vol	0.000020	0.000203
HC	168.0	ppm	0.000001	0.000011
NO <sub>x</sub>	250.0	ppm	0.000005	0.000046

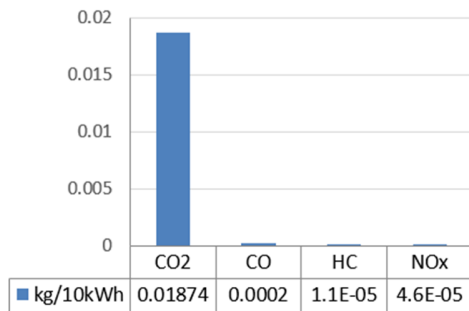


Fig. 4. Emissions using biogas as fuel.

C. Generator Emissions Using LPG

The emissions from the 1 kW SIE running on LPG, along with the calculated values for the 10 kW SIE, are outlined in Table III. CO<sub>2</sub> was the highest pollutant, indicating near-complete combustion of LPG. The values for CO and HC were relatively low, as expected, given the purity and composition of clean LPG. NO<sub>x</sub> also appeared at moderate values, reflecting the relatively high combustion temperatures. These results demonstrate relatively low pollutant emissions compared to biogas, reflecting high combustion efficiency and fuel purity. These emissions are illustrated in Figure 5.

TABLE III. EMISSIONS GENERATED FROM BURNING SYNGAS IN 1 KW SIE

Gas	Value	Unit	kg/kWh	kg/10kWh
CO <sub>2</sub>	11.2	% vol	0.001980	0.019804
CO	0.15	% vol	0.000017	0.000169
HC	130.0	ppm	0.000001	0.000008
NO <sub>x</sub>	240.0	ppm	0.000004	0.000044

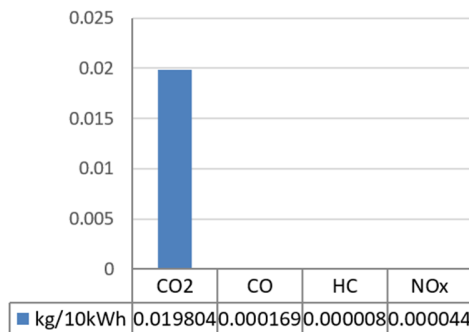


Fig. 5. Emissions using LPG as fuel.

In this study, the performance of a 10 kW SIE fueled by syngas, biogas, and LPG was evaluated, and the results showed varying emission profiles and combustion efficiencies. The CO<sub>2</sub> emissions from syngas were notably higher than those from LPG and biogas, with pure wood syngas emitting up to 3.78 kg/kWh CO<sub>2</sub> compared to 0.00198 kg/kWh for LPG and 0.00187 kg/kWh for biogas. This aligns with the findings of a previous study, which also reported higher CO<sub>2</sub> emissions from syngas, particularly when derived from biomass sources, such as wood [8]. Similarly, the CO emissions were significantly higher when syngas was used, reflecting incomplete combustion, which is consistent with [7], where similar results were observed when comparing producer gas with conventional fuels. In contrast, LPG and biogas exhibited much lower CO emissions, suggesting better combustion efficiency. Regarding the unburned HCs, syngas, especially from mixtures of wood and corn, showed the highest HC levels, indicating incomplete combustion. This result is in line with [4], where higher HC emissions were found when producer gas was used compared to other fuels. In contrast, both LPG and biogas showed minimal HC emissions, confirming their more efficient combustion profiles. Overall, while syngas shows potential for energy production, its emissions, particularly those of CO<sub>2</sub>, CO, and HC, are higher than those of biogas and LPG, which are considered more efficient and cleaner alternatives for internal combustion engines.

The results show that the pollutant emissions, particularly CO<sub>2</sub>, CO, and NO<sub>x</sub>, from operating an internal combustion generator using syngas are relatively higher than those from conventional fuels, such as LPG and biogas, as listed in Table IV.

TABLE IV. SYNGAS PERFORMANCE COMPARED WITH OTHER FUELS

Pollutant	LPG (kg/kWh)	Biogas (kg/kWh)	Syngas (highest value) (kg/kWh)
CO <sub>2</sub>	0.001980	0.001874	3.7821
CO	0.000017	0.000020	0.0373
HC	0.000001	0.000001	0.00235
NO <sub>x</sub>	0.000004	0.000005	0.0132

The emissions of the syngas fuels may seem high, as shown in Figure 6. However, they reflect the practical nature of the composition of syngas produced from the gasification of biomass, such as wood and corn. The high concentrations of pollutants do not necessarily indicate a poor fuel, but rather a complex chemical reaction and gas heterogeneity, opening the door to developing purification processes and improving the combustion performance. Syngas is a renewable fuel produced from agricultural waste or wood residues, reducing the dependence on fossil fuels. This allows the utilization of local waste and its conversion into thermal and electrical energy, supporting a circular economy. Although the syngas emissions are relatively high, its performance can be improved by using filters to remove the tar and particulate matter. Adjusting the air/fuel ratio in the generator is also important. Designing specialized generators to operate efficiently on syngas.

This study demonstrates that the combustion of syngas (which includes a mixture of gases such as CO and H<sub>2</sub>) in SIEs

suffers from challenges in terms of thermal stability and combustion efficiency issues. In this context, the findings of the current study are consistent with those of [9], where the effects of CO/H<sub>2</sub> mixtures on the combustion in a SIE were examined. It has been demonstrated that adding hydrogen to syngas enhances the flame temperature and stability, leading to improved overall combustion efficiency [9]. This is consistent with the findings of this study, indicating that increasing the hydrogen content in syngas improves the thermal efficiency and reduces the risks associated with incomplete combustion. These findings underscore the need to optimize the syngas mixtures to achieve better internal combustion engine performance.

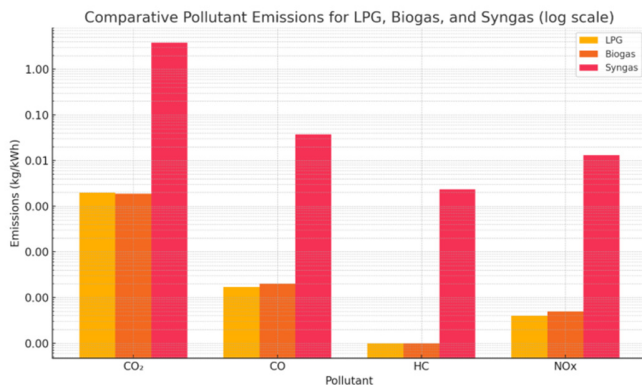


Fig. 6. Comparative pollutant emissions of LPG, biogas, and syngas.

Authors in [10] studied the exothermic analysis of internal combustion engines powered by Compressed Natural Gas (CNG), and blended CNG with hydrogen, and showed that the latter enhanced the engine's exothermic efficiency and reduced the exothermic losses compared to natural gas and HCNG. These findings are consistent with the present study's results, which showed that increasing the hydrogen content in the syngas blend improves the combustion efficiency and reduces the energy losses. In addition, future studies comparing syngas and hydrogen could contribute to improving the exergy performance of engines.

#### IV. CONCLUSIONS

In this study, the performance of internal combustion engines powered by syngas, biogas, and Liquefied Petroleum Gas (LPG) was evaluated, focusing on the emissions and fuel consumption. The results showed that syngas, particularly from wood, produced higher CO<sub>2</sub> emissions than LPG and biogas, in agreement with the literature. Additionally, similar trends were observed in terms of increased fuel consumption and CO<sub>2</sub> emissions [11]. The previous studies and this study's results highlight the need for further optimization of alternative fuels, such as syngas, to improve the combustion efficiency and reduce the environmental impact.

Despite the higher emissions from syngas, employing strategies, like catalytic tar cracking, optimized air-fuel ratios, and combustion chamber modifications can significantly reduce the pollutants, making syngas a viable low-emission

fuel for decentralized energy systems. Therefore, syngas can be considered a practical solution in rural areas where agricultural waste is available, provided that combustion technologies are developed to reduce the emissions.

Future research should focus on long-term engine durability tests and economic feasibility studies to evaluate the practical implementation of biomass-derived fuels in decentralized power systems, providing insights into the sustainability and cost-effectiveness of these technologies.

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