

## Review Article

# Performance and Emission Characteristics of a Spark Ignition Engine Fueled with Gasoline–Bioethanol Blends Derived from Different Biomass Sources

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**Citation** N. Yunusa, A.F. Ali, M.H. Ibrahim, Y. Adamu, N.I. Adamu. Performance and Emission Characteristics of a Spark Ignition Engine Fueled with Gasoline–Bioethanol Blends Derived from Different Biomass Sources. *J. Eng. Ind. Res.* 2026, 7 (2):139-148.

 <https://doi.org/10.48309/JEIRES.2026.536226.1270>



## Article info:

Submitted: 2025-07-22

Revised: 2025-10-22

Accepted: 2025-11-16

ID: JEIRES-2507-1270

## Keywords:

Bioethanol–gasoline blends; Spark ignition engine; Engine performance; Emission characteristics; NO<sub>x</sub> emissions; Thermal efficiency.

## ABSTRACT

The growing need for cleaner energy sources has positioned bioethanol as a viable alternative to gasoline in spark-ignition engines. This overview examines how blending gasoline with bioethanol from diverse feedstocks like sugarcane, corn, lignocellulosic materials, and algae impacts engine performance and emissions. Bioethanol's high oxygen content and octane rating enhance combustion, reducing carbon monoxide and hydrocarbon emissions. However, its lower energy density may compromise power output and efficiency. The effect on nitrogen oxides (NO<sub>x</sub>) is condition-dependent: while certain blends (E10–E20) may lower NO<sub>x</sub> due to cooler combustion, higher blends or specific load conditions can increase NO<sub>x</sub> formation. Blends containing 10–30% ethanol typically improve thermal efficiency and reduce emissions without requiring significant engine modifications. Higher ethanol blends might increase fuel consumption and cold-start difficulties. While second-generation bioethanol offers substantial environmental advantages, its production poses challenges. This review identifies the key research gap: the need to optimize higher ethanol blends and clarify NO<sub>x</sub> behavior under different operating conditions. Blends with up to 30% ethanol strike a balance between performance and sustainability, making them a practical choice.

## Introduction

Spark ignition (SI) engines remain one of the most widely used power sources for transportation and small-scale applications due to their simplicity, low cost, and reliability. However, their reliance on fossil fuels has raised concerns

about energy security, rising fuel prices, and environmental impacts. The combustion of gasoline in SI engines contributes significantly to greenhouse gas (GHG) emissions and air pollutants such as carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO<sub>x</sub>), and particulate matter, which negatively affect both human health and the environment

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[1]. These challenges have motivated global interest in renewable and cleaner alternatives to fossil fuels. Among the various biofuels, bioethanol has emerged as a promising candidate for blending with gasoline. Bioethanol is a renewable alcohol fuel that can be produced from a variety of biomass sources. Its chemical and physical properties—such as high oxygen content, high octane rating, and good miscibility with gasoline—make it suitable for use in SI engines with minimal or no modifications [2]. The high oxygen content of ethanol improves combustion efficiency, leading to reduced emissions of CO and HC, while the high octane rating enhances anti-knock performance, allowing for smoother and more efficient engine operation [3-5]. However, ethanol's lower energy density compared to gasoline can result in higher fuel consumption at higher blend ratios.

Research Gap and Objective: While extensive studies exist on ethanol-gasoline blends, most focus on first-generation ethanol. Limited reviews compare different biomass sources and their influence on performance and emissions. Furthermore, inconsistencies remain in reported NO<sub>x</sub> trends and the practical optimization of higher ethanol blends. This review therefore aims to critically analyze how ethanol concentration and biomass feedstock type influence performance and emissions in SI engines, identify the unique sustainability impacts of feedstock type, and highlight unresolved research challenges.

### **Bioethanol Production from Biomass Sources**

Bioethanol, a renewable and biodegradable fuel, is commonly used in spark ignition engines as a gasoline alternative [6]. Its production efficiency, yield, and sustainability largely depend on the type of biomass feedstock used, which falls into three categories: first-, second-, and third-generation sources [7].

#### *First-generation (sugar- and starch-based)*

These sources include crops like sugarcane, corn, and wheat, which contain easily fermentable sugars or starch. Starches are first hydrolyzed into sugars before fermentation [8].

#### *Advantages*

- High ethanol yield,
- Mature and efficient technology, and
- Fast fermentation [9].

#### *Disadvantages*

- Competes with food supply,
- Requires large land and water use, and
- Potential for environmental impacts [10].

#### *Second-generation (lignocellulosic biomass)*

- It includes crop residues, forestry waste, and energy crops. These require complex pretreatment and enzymatic hydrolysis to convert cellulose and hemicellulose into fermentable sugars [11].

#### *Advantages*

- Non-food, abundant feedstocks,
- Reduced land-use conflict, and
- Higher GHG reduction potential [12].

#### *Disadvantages*

- Technically and economically demanding,
- Lower fermentation efficiency, and
- Limited large-scale viability [13].

As summarized in Table 1, the advantages and disadvantages of different bioethanol feedstock generations are compared.

**Table 1:** Shows generations pros and cons of different feedstocks [17,18]

Generation	Feedstock type	Process involved	Advantages	Disadvantages
1 <sup>st</sup>	Sugarcane, corn, and wheat	Fermentation (after hydrolysis)	High yield, mature technology	Food vs. fuel, land and water use
2 <sup>nd</sup>	Agricultural/forestry waste	Pretreatment → hydrolysis → fermentation	Abundant, sustainable, non-food	Costly, complex processing
3 <sup>rd</sup>	Algae, microalgae	Hydrolysis or gasification + fermentation	High yield potential, non-arable land use	Expensive, not yet commercialized

**Table 2:** Properties and units of gasoline–ethanol blends (E0–E30)

Property	Unit	Gasoline (E0)	E10	E20	E30
Density (15 °C)	kg/m <sup>3</sup>	740–770	760	780	800
Specific gravity	–	0.74–0.77	0.76	0.78	0.80
Calorific value	MJ/kg	44.0	42.2	41.6	41.3
Octane number (RON)	–	91–95	96	100	104
Oxygen content	wt.%	0	3.5	7.0	10.5
Reid vapor pressure (RVP)	kPa	60–70	63	58	55
Viscosity (40 °C)	mm <sup>2</sup> /s	0.4–0.8	0.9	1.1	1.3
Flash point	°C	-43	-20	-5	+10
Stoichiometric A/F ratio	–	14.7	13.8	13.1	12.5
Vaporization heat	kJ/kg	350	500	620	710

### Third-generation (algal biomass)

- Derived from carbohydrate-rich algae, particularly microalgae, which are processed via hydrolysis or gasification and fermentation [14].

#### Advantages

- Fast growth and high productivity,
- No competition with food or farmland, and
- Effective CO<sub>2</sub> absorption [15]

#### Disadvantages

- High cost of cultivation and processing, and
  - Low commercial availability.
- Technical barriers in scaling and yield improvement [16–18]

### Properties of Gasoline–Bioethanol Blends

As presented in Table 2, blending ethanol with gasoline alters several key fuel properties, affecting combustion, engine performance, and emissions. These changes vary with ethanol content (e.g., E5, E10, and E20) [19].

### Discussion

The properties of gasoline–bioethanol blends differ significantly from those of pure gasoline, primarily due to the polar nature and oxygen-rich composition of ethanol. These variations influence combustion behavior, fuel economy, and emissions in spark ignition (SI) engines.

#### Density and specific gravity

The density of the blend increases with ethanol concentration because ethanol is denser than gasoline. This higher density slightly increases the mass of fuel delivered per injection cycle, potentially improving combustion efficiency but may require calibration adjustments for fuel metering systems.

#### Calorific value

The energy content decreases as ethanol proportion rises. For instance, while gasoline's calorific value is around 44 MJ/kg, E30 can drop to approximately 41.3 MJ/kg. This reduction often leads to increased brake specific fuel

consumption (BSFC) since more fuel mass is needed to produce the same power output.

### *Octane rating*

Ethanol's high octane number ( $\approx 108$  RON) significantly improves the overall blend's anti-knock property. This allows the engine to operate with higher compression ratios and advanced ignition timing, enhancing thermal efficiency and performance at moderate blend ratios (E10–E30).

### *Oxygen content and combustion*

Ethanol introduces oxygen into the fuel, enhancing oxidation of CO and HC during combustion. As a result, blends up to E30 typically exhibit lower CO and HC emissions compared to pure gasoline. However, the higher oxygen content may also promote higher flame temperatures, contributing to increase  $\text{NO}_x$  formation at elevated ethanol levels.

### *Reid vapor pressure (RVP)*

RVP initially increases at low blend ratios (E10), improving cold-start capability. Beyond E10, it tends to decline due to ethanol's lower volatility compared to gasoline, which can affect vaporization at low ambient temperatures.

### *Viscosity and flash point*

Ethanol slightly increases the viscosity and flash point of the blend. A higher flash point reduces the risk of accidental ignition, improving handling safety, while increased viscosity aids lubrication of fuel system components.

### *Stoichiometric air–fuel ratio*

The stoichiometric air–fuel ratio decreases from 14.7 for gasoline to about 12.5 for E30. This means richer mixtures are needed for complete combustion, which can impact mixture preparation and tuning requirements.

### *Latent heat of vaporization*

Ethanol's high latent heat cools the intake charge, increasing volumetric efficiency and reducing knocking tendency. This cooling effect can enhance brake thermal efficiency (BTE) at moderate blends, though it may cause cold start issues in colder climates.

Overall, E10–E30 blends provide an optimal compromise between performance, emissions, and fuel economy. They enhance octane rating, promote cleaner combustion, and maintain acceptable energy output without major engine modifications. However, higher ethanol contents may lead to phase separation, higher BSFC, and  $\text{NO}_x$  formation, particularly if not properly blended or used in unmodified engines.

### *Octane rating*

Ethanol has a high octane number ( $\sim 108$  RON), improving resistance to engine knock. Blends such as E10 and E20 enhance combustion efficiency and allow higher compression without engine modifications [20].

### *Vapor pressure*

Low ethanol blends (E5–E10) can raise vapor pressure, increasing evaporative emissions. However, at higher ethanol levels (E20+), vapor pressure decreases again. Managing this is essential for cold starts and fuel system compatibility [21].

### *Oxygen content*

With approximately 35% oxygen by weight, ethanol promotes more complete combustion, reducing CO and HC emissions. Higher ethanol blends further increase oxygen content, leading to cleaner exhaust gases [22].

### *Energy content*

Ethanol has a lower energy density (21–23 MJ/L) than gasoline (32–34 MJ/L). This results in higher fuel consumption at higher blend levels (e.g., E20 and E30) to maintain the same power output [23].

### Common blend ratios and their significance

E5 and E10: Widely adopted in many countries due to compatibility with existing engines and infrastructure. These blends offer modest reductions in CO and HC emissions with minimal impacts on fuel economy [24,25].

E15 and E20: Provide higher octane and oxygen content, potentially improving thermal efficiency and reducing certain emissions, but may require engine tuning or calibration for optimal performance [26,27].

E25 and E30: Considered high-level blends, these are often used in flexible-fuel vehicles (FFVs). They significantly improve combustion quality but may lead to increased fuel consumption due to lower energy content [28,29].

Each blend level affects engine operation differently. Lower blends (E5–E10) are drop-in fuels, requiring no modification, while higher blends (E20–E30 and beyond) may necessitate changes to fuel systems, injectors, and engine control units [30,31].

### Performance Characteristics of Ethanol-Gasoline Blends in SI Engines

Ethanol's high octane rating, oxygen content, and heat of vaporization influence key engine

performance metrics (as presented in Table 3). The effects vary with blend ratios and operating conditions [34,35].

#### Brake thermal efficiency (BTE)

Ethanol blends (typically E20–E30) improve BTE due to enhanced combustion and knock resistance, leading to better energy conversion. Beyond E30, gains diminish due to ethanol's lower energy density [36,37].

#### Brake specific fuel consumption (BSFC)

Ethanol's lower energy content increases BSFC at higher blends (E20+). However, blends up to E20 may offset this with improved combustion efficiency, especially at moderate loads [38,39].

#### Torque and power output

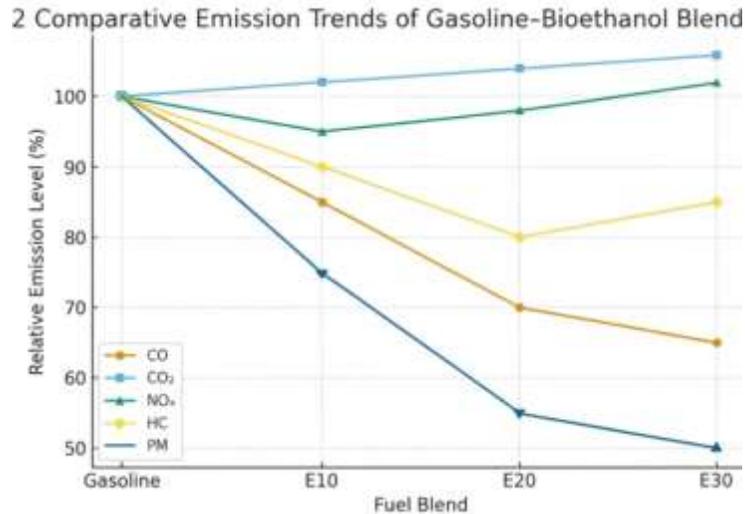
Ethanol cools the intake mixture, improving air density and volumetric efficiency. Blends like E10 and E20 often yield slight increases in torque and power. At higher blends (E40+), power may decline unless compensated by engine adjustments (see Table 4 for a summary of performance variations across blends) [40,41].

**Table 3:** Comparative properties of gasoline–ethanol blends (E10–E30) [32,33].

Property	Gasoline	Ethanol	E10	E20	E30
Octane number (RON)	91–95	~108	~93–96	~95–98	~97–100
Energy content (MJ/L)	32–34	21–23	~30.5	~29	~27.5
Oxygen content (wt%)	0	~35	~3.5	~7.0	~10.5
Vapor pressure (kPa)	~60–75	~16	Slightly higher for E10	Variable for E20	Slightly lower for E30

**Table 4:** Performance metrics of gasoline–ethanol blends (E10–E30) [48,49].

Performance metric	Unit	Gasoline	E10	E20	E30
Brake thermal efficiency (BTE)	%	Baseline	+1–3%	+3–6%	+4–8%
Brake specific fuel consumption (BSFC)	g/kWh	Baseline	+2–5%	+5–10%	+10–15%
Torque	Nm	Baseline	+1–3%	+2–5%	≈ Same or slightly ↓
Power output	kW	Baseline	+2%	+3–4%	~ 0 or slightly ↓



**Figure 1:** Comparative emission trends of gasoline–bioethanol blends in SI engines

### Effect of different ethanol concentrations

Low-level blends (E5–E10): Minimal modifications required. Typically maintain or slightly improve efficiency and power while reducing CO and HC emissions [42,43].

Mid-level blends (E15–E30): An optimal balance between power output, BTE, and emissions reduction. ECU recalibration may be required [44,45].

High-level blends (E40+): Lower net energy content leads to higher fuel consumption unless engine is optimized for ethanol (*e.g.* in FFVs or dedicated ethanol engines) [46-49].

### Emission Characteristics of Ethanol–Gasoline Blends in SI Engines

Ethanol's oxygen-rich structure and clean-burning properties significantly influence emission levels in spark ignition (SI) engines. Effects vary with blend ratio and operating conditions [50].

Figure 1 illustrates the comparative emission behavior of gasoline–bioethanol blends in a spark ignition (SI) engine. As ethanol concentration increases, carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM) emissions decline significantly due to the enhanced oxygen content and cleaner combustion characteristics of ethanol. Carbon dioxide (CO<sub>2</sub>) emissions show a modest rise

because of improved combustion efficiency, although the overall carbon footprint may still be lower when ethanol's renewable origin is considered. Nitrogen oxides (NO<sub>x</sub>) exhibit a non-linear pattern—slightly decreasing at low blend ratios (E10–E20) and rising again at higher levels (E30) because of elevated in-cylinder temperatures during combustion. These findings align with previous studies [51-53] confirming ethanol's beneficial role in reducing harmful exhaust emissions from SI engines.

### Carbon monoxide (CO)

Ethanol enhances combustion efficiency, reducing CO emissions—especially with blends up to E30—by promoting better oxidation [54,55].

### Carbon dioxide (CO<sub>2</sub>)

While improved combustion may raise CO<sub>2</sub> output, ethanol's lower carbon content and renewable origin can reduce overall CO<sub>2</sub> emissions per kilometer [56].

### Nitrogen oxides (NO<sub>x</sub>)

Ethanol blends (E10–E20) may lower NO<sub>x</sub> due to cooler combustion, though higher blends can

slightly raise NO<sub>x</sub> under lean or high-load conditions [57].

### Unburned hydrocarbons (HC)

Moderate blends (E10–E20) reduce HC emissions due to better combustion, but cold-start HC can rise with higher blends because of ethanol's low volatility [58].

### Particulate matter (PM)

Low aromatic content in ethanol reduces PM emissions significantly—E20–E30 blends can cut PM mass and particle numbers by up to 60%.

### Conclusion

This review has examined the performance and emission characteristics of spark ignition engines fueled with gasoline–bioethanol blends derived from various biomass sources. Ethanol blending, particularly within the E10–E20 range, reduces fossil fuel consumption and emissions of CO, HC, and particulate matter while modestly improving brake thermal efficiency without requiring major engine modifications. Although higher blends such as E30–E85 can further reduce certain emissions, they are often associated with increased fuel consumption, cold-start difficulties, and the need for engine adaptation or flex-fuel technology. A major limitation identified in this review is the inconsistent reporting of NO<sub>x</sub> emissions, which remain highly condition-dependent. Another limitation is the lack of large-scale economic feasibility studies for second- and third-generation bioethanol.

### Acknowledgement

The author would like to thank Almighty Allah for the strength and guidance throughout this research. The sincere appreciation goes to the supervisors, [Prof. Habu Dandakuta and Dr. Abubakar Ali Fachway], for their support and valuable inputs. The author would also acknowledge the staff of Mechanical/Production Engineering for their assistance, and his family and friends for their constant encouragement. Lastly, he would like to appreciate all

researchers whose work contributed to this study.

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