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Original article

Effect of Agricultural Waste-Derived Biomethanol Use on the Performance and Emission Characteristics of a Diesel Engine

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Abstract

This study investigates the effects of wheat straw-derived biomethanol–diesel blends on the performance and emission characteristics of a diesel engine. Four fuel blends were tested: pure diesel (D100) and biomethanol blends at volumetric ratios of 5%, 10%, and 15% (B5, B10, B15). Experiments were conducted on a single-cylinder diesel engine under four load conditions (25%, 50%, 75%, and 100%). The results show that although the lower heating value of biomethanol increased specific fuel consumption (from 308 g/kWh to 346 g/kWh at full load), its high oxygen content and latent heat of vaporization significantly improved key emission parameters. Under full load, the B15 blend reduced exhaust gas temperature by 29 °C, soot emissions by 25%, and CO emissions by approximately 21% compared to D100. Conversely, nitrogen oxide (NOx) emissions increased from 2165 ppm to 2420 ppm, attributed to the ignition delay characteristics of biomethanol. Overall, blending biomethanol with diesel is an effective strategy for reducing soot and CO emissions; however, further optimization is required to address the trade-off between NOx emissions and fuel consumption.

Keywords: Biomethanol, Wheat Straw, Diesel Engine, Specific Fuel Consumption, Alternative Fuels

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INTRODUCTION

The continuous growth in global energy demand and the rapid depletion of conventional fossil fuel reserves have directed researchers toward sustainable and renewable alternative energy sources (Demirbas, 2007). Diesel engines are widely used in agricultural machinery, heavy vehicles, and industrial power systems due to their high thermal efficiency and durability, making them central to the ongoing energy transition. However, nitrogen oxides (NOx), carbon monoxide (CO), and particulate matter (soot/smoke) produced during diesel combustion pose serious threats to both the environment and human health, driving increasingly stringent international emission standards such as the EURO norms (Mofijur et al., 2019; Reif, 2014). To overcome this environmental challenge, the use of alternative and clean-burning biofuels has emerged as one of the most promising and feasible strategies, alongside mechanical improvements in engine design (Agarwal, 2007).

In recent years, second-generation biofuels — which avoid competition with food production and land use — have gained considerable importance in the context of sustainable agriculture and circular economy policies. In countries with high agricultural output such as Turkey, lignocellulosic residues like wheat straw represent a substantial biomass energy reserve (Saygin & Gielen, 2021). Converting such agricultural wastes into biomethanol via thermochemical or biochemical pathways not only offers an innovative approach to waste management but also yields a high-value, clean engine fuel.

The high oxygen content (~50%) in the molecular structure of methanol is known to enhance combustion efficiency and significantly influence soot formation and oxidation reactions (Öztürk & Canlı, 2022; Uyumaz, 2020). Nevertheless, the high latent heat of vaporization of methanol can reduce in-cylinder temperatures, creating a dual effect on thermal efficiency. Its low cetane number and lower heating value increase ignition delay, which may lead to elevated NOx emissions under certain operating conditions (Atmanlı et al., 2015; Yılmaz et al., 2021). In recent years, methanol has attracted significant research interest as an alternative fuel for diesel engines due to its potential to mitigate emissions and improve thermal efficiency. Several studies (Hassan & Al-Abboodi, 2024; Kadhim & Oshchepkov, 2024; Kumar & Krishnamoorthi, 2025) have evaluated the performance and emission characteristics of methanol–diesel blends under various load conditions, demonstrating methanol's potential as a sustainable fuel candidate for compression ignition engines. Despite the extensive literature on diesel–alcohol blends, studies specifically examining the combined effects of biomethanol synthesized directly from an agricultural waste — wheat straw — on the thermodynamic performance and emission profile of a diesel engine across multiple volumetric ratios and load conditions remain limited.

This study aims to address this gap by integrating agricultural waste-derived biomethanol into diesel engine applications. Biomethanol produced from wheat straw was blended with pure diesel at volumetric ratios of 5%, 10%, and 15% (B5, B10, B15). The effects of these blends on specific fuel consumption, exhaust gas temperature, and key exhaust emissions (CO, NOx, soot) were experimentally

evaluated on a single-cylinder diesel engine at four load stages (25%, 50%, 75%, and 100%) and compared against the reference diesel fuel (D100). The findings are expected to provide valuable engineering data on the commercial viability of agricultural waste-derived biofuels in engine applications.

MATERIALS AND METHODS

Experimental Setup and Equipment

Experiments were conducted on a single-cylinder, four-stroke diesel engine (Erin Motor) commonly used in agricultural applications in Turkey, particularly in irrigation pump systems. To accurately determine engine performance parameters (brake power, torque, etc.), an APICOM eddy current dynamometer was integrated into the test setup. The schematic layout and measurement precision of the system were configured in accordance with internal combustion engine testing standards (Reif, 2014).

A National Instruments (NI) data acquisition system was used for real-time monitoring and digital recording of engine and dynamometer data throughout the experiments. Temperatures at critical engine components and along the exhaust line were measured using high-precision PT100 sensors and K-type thermocouples. Fuel consumption was determined gravimetrically using a precision balance, while exhaust emissions (CO, NOx, and soot) were measured with a Bosch five-gas analyzer meeting industrial measurement standards. To minimize total measurement uncertainty, error analysis protocols recommended in the literature were applied to all instruments prior to testing (Holman, 2012). The schematic representation of the experimental system is given in Figure 1, the technical specifications of the test engine are listed in Table 1, and the measurement devices with their accuracies are presented in Table 2.

Table 1. Technical specifications of the test engine

General Characteristics	**Technical Specifications**
Engine type	Erin Motor Base Model
Number of Valves	4
Continuous Power (kw/rpm)	11.5 / 1500
Bore (mm)	108
Stroke (mm)	127
Combustion System	Direct Injection
Compression Ratio	14.6:1
Engine Cooling	Water
Weight (kg)	157

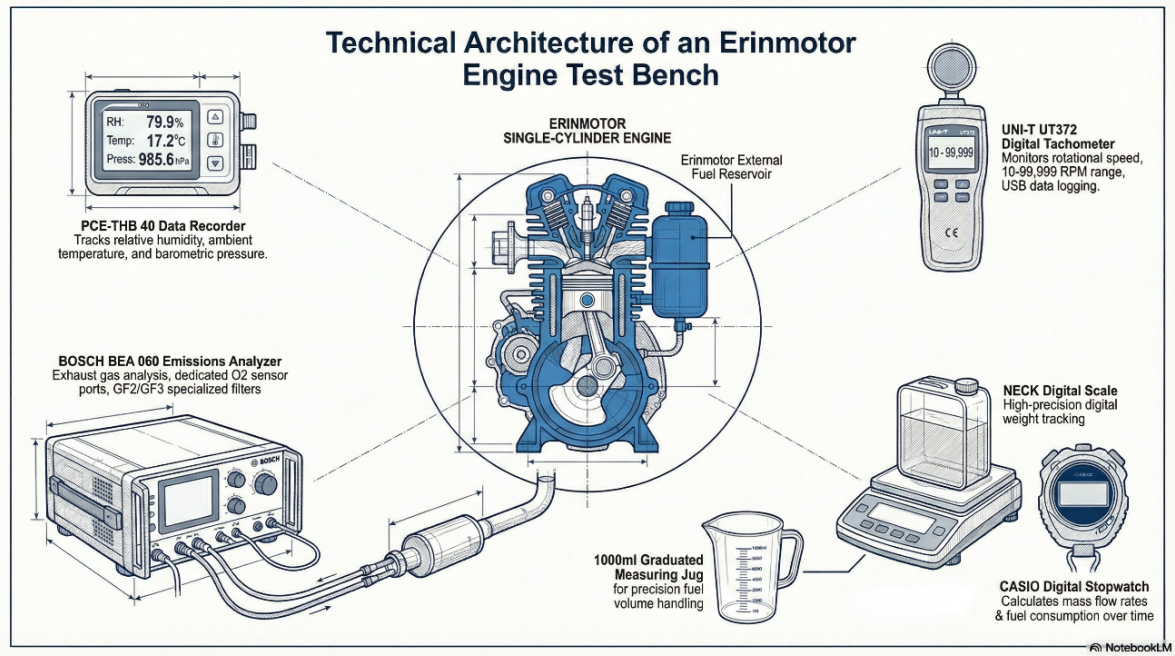


Figure 1. Test system

Table 2. Measurement devices' accuracy and associated uncertainties

Measured Parameter	Accuracy / Sensitivity	Uncertainty / Tolerance	Notes	Brand/Model
Dynamometer	± 0.03 kg	± 0.02kg	Resolution and calibration-related uncertainty	API-COM FR50
Shaft Speed (rpm)	1 rpm	± 0.5%	Includes resolution and repeatability uncertainty	UNI-T UT372
Fuel Flow Time (s)	± 0.1 s	± 0.1 s	Chronometer precision	CASIO Hs-3v-1rdt
Exhaust Gas Temperature (°C)	± 0.1 °C	-	K-type thermocouple precision	NR 81539
CO (%vol)	0.001%vol	± 0.005%vol	Device sensitivity combined with tolerance	Bosch BEA 60
NOx (ppm vol)	1 ppm vol	± 12 ppm	Device sensitivity combined with tolerance	Bosch BEA 60
Bosch Smoke Number(BSN)	0.1	± 0.2 BSN	Device sensitivity combined with tolerance	Bosch BEA 70

Preparation of Fuel Blends

In this study, standard commercial diesel fuel (D100) was used as the base fuel, and second-generation biomethanol derived from wheat straw biomass served as the blending component. Fuel blends were prepared by adding biomethanol to diesel at volumetric ratios of 5% (B5), 10% (B10), and 15% (B15). To prevent phase separation and stability issues commonly reported for diesel–alcohol mixtures in the literature (Yılmaz et al., 2021), each blend was mechanically mixed in a 5-liter container for approximately 10 minutes at room temperature (25 ± 2 °C) immediately prior to testing. No chemical

surfactants or co-solvents were added, so as to isolate the pure effects of the biomethanol–diesel blends. Since methanol–diesel mixtures are prone to phase separation during prolonged storage, all prepared blends were fed directly into the fuel system and consumed immediately after preparation. The blend compositions and fuel abbreviations are given in Table 3, and the physical and chemical properties of the test fuels are presented in Table 4.

Table 3. Fuel ratios and abbreviations.

Abbreviation	Diesel (%)	Bio-Methanol (%)
D100	100	0
B5	95	5
B10	90	10
B15	85	15

Table 4. Physical and chemical properties of test fuels

Property	Diesel (D100)	Biomethanol
Chemical Formula	C_{12}–C_{20} (approx.)	CH_3OH
Lower Heating Value (LHV) (MJ/kg)	42–43	19.9
Density at 15°C (kg/m³)	820–840	790
Kinematic Viscosity (mm²/s at 40°C)	2.0–4.5	0.6
Cetane Number	45–55	3–5
Oxygen Content (% wt)	~0	49.9
Latent Heat of Vaporization (kJ/kg)	~250	~1100
Stoichiometric A/F Ratio	14.5	6.4

Test Procedure

Performance and emission tests were carried out at a constant engine speed of 1500 rpm, which represents the characteristic operating point of the test engine. To ensure repeatability and measurement accuracy, the engine was warmed up using the reference fuel (D100) until oil and coolant temperatures reached nominal operating values. Once thermal equilibrium was established, the engine was tested sequentially at four load stages: 25%, 50%, 75%, and 100% (full load). At each load condition and for each fuel blend, the engine was allowed to reach a stable operating regime before power output, exhaust gas temperature, specific fuel consumption, and emission values were recorded simultaneously (Uyumaz, 2020). Each test condition was repeated three times to ensure data reliability and repeatability, and the mean values were used in the final analysis.

RESULTS AND DISCUSSION

In this section, the effects of biomethanol–diesel blends at ratios of 5%, 10%, and 15% (B5, B10, B15) on the performance and emission characteristics of a single-cylinder diesel engine are presented

and discussed. All results are compared against the reference diesel fuel (D100). As reported in the literature, the use of oxygenated fuels such as biomethanol in diesel engines generally improves combustion quality; however, differences in fuel chemical properties produce complex effects on thermodynamic efficiency and emission formation mechanisms (Öztürk & Canlı, 2022). The trends observed in this study are interpreted in light of the low heating value, high latent heat of vaporization, and molecular oxygen content of biomethanol (Uyumaz, 2020; Yılmaz et al., 2021).

Specific Fuel Consumption (SFC)

According to the data obtained from the engine tests (Figure 2), it was observed that the increase in the biomethanol ratio triggered an upward trend in specific fuel consumption (SFC) at all load stages. The consumption value, measured as 308 g/kWh for the reference diesel (D100) under full load (100%) conditions, increased to the levels of 315 g/kWh with 5% biomethanol (B5), 331 g/kWh with 10% biomethanol (B10), and 346 g/kWh with the addition of 15% biomethanol (B15).

This situation is explained in the literature by the fact that alcohol-based fuels have a lower heating value (LHV) compared to diesel fuel (Öztürk & Canlı, 2022). Since the energy content per unit mass of biomethanol is less than that of diesel, it becomes mandatory to increase the amount of fuel that must be sent into the cylinder per unit time in order to provide a constant engine power output (Uyumaz, 2020). This increasing trend exhibits a graph directly proportional to the alcohol concentration in the fuel blend (Yılmaz et al., 2021). In addition, the lower viscosity and density of biomethanol compared to diesel are considered a secondary factor supporting this increase in specific fuel consumption by affecting leakages and injection flow rate in the fuel injection system (Atmanlı et al., 2015). Consequently, in the use of wheat straw-derived biomethanol, an increase in fuel consumption to meet the energy amount required by the engine is an expected thermodynamic result.

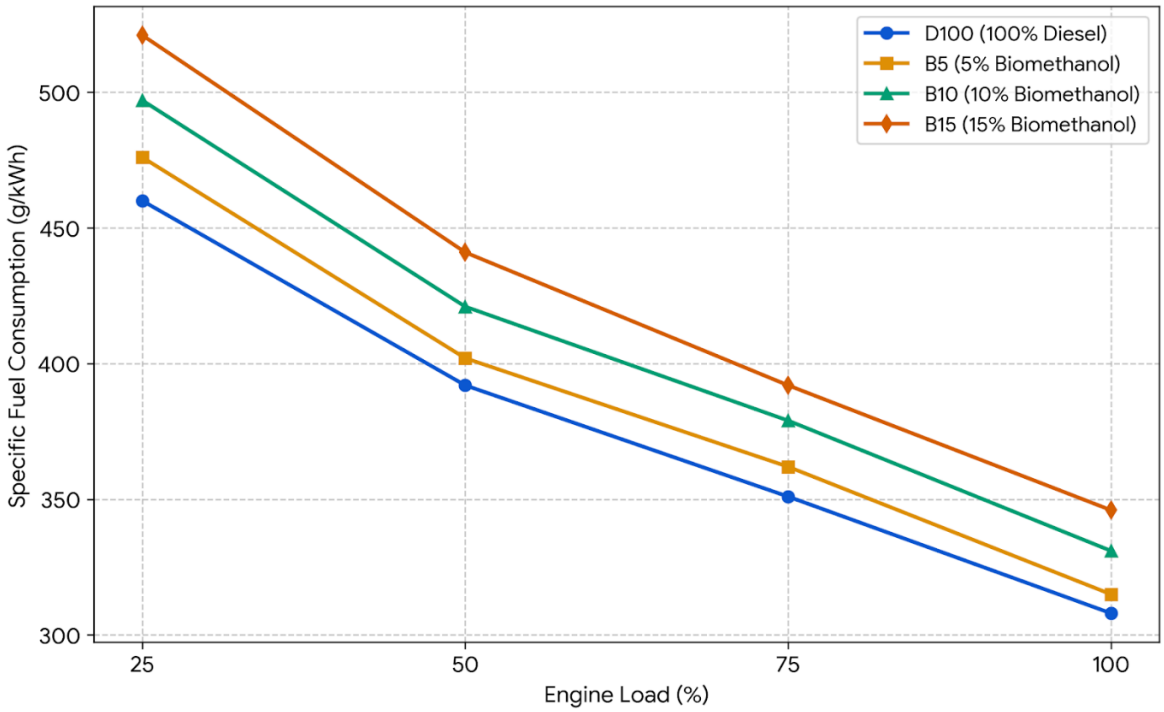


Figure 2. Specific fuel consumption of the test fuels at different engine loads.

Exhaust Gas Temperature (EGT)

The experimental results (Figure 3) show that parallel to the increase in engine load, exhaust gas temperatures increased for all fuel blends, but the addition of biomethanol systematically decreased these temperature values. The exhaust temperature, measured as 595 °C with the use of pure diesel (D100) under full load (100%) conditions, decreased to the levels of 584 °C with 5% biomethanol (B5), 576 °C with 10% biomethanol (B10), and 566 °C with the addition of 15% biomethanol (B15).

This decrease observed in the exhaust gas temperature is explained in the literature by the considerably high latent heat of vaporization of biomethanol compared to diesel (Atmanlı et al., 2015). The thermal energy absorbed by alcohol-based fuels from the in-cylinder environment during the vaporization phase causes a decrease in end-of-combustion temperatures and, consequently, the discharge of the exhaust gas at lower temperatures (Köse et al., 2022). In addition, the lower heating value (LHV) of biomethanol, which is lower than that of diesel, limits the total amount of heat released per cycle, supporting this decreasing trend (Özener et al., 2014). This decrease in EGT values is of importance in terms of reducing the thermal stress on engine components and keeping the nitrogen oxide (NOx) emissions, which occur especially due to high temperatures, under control.

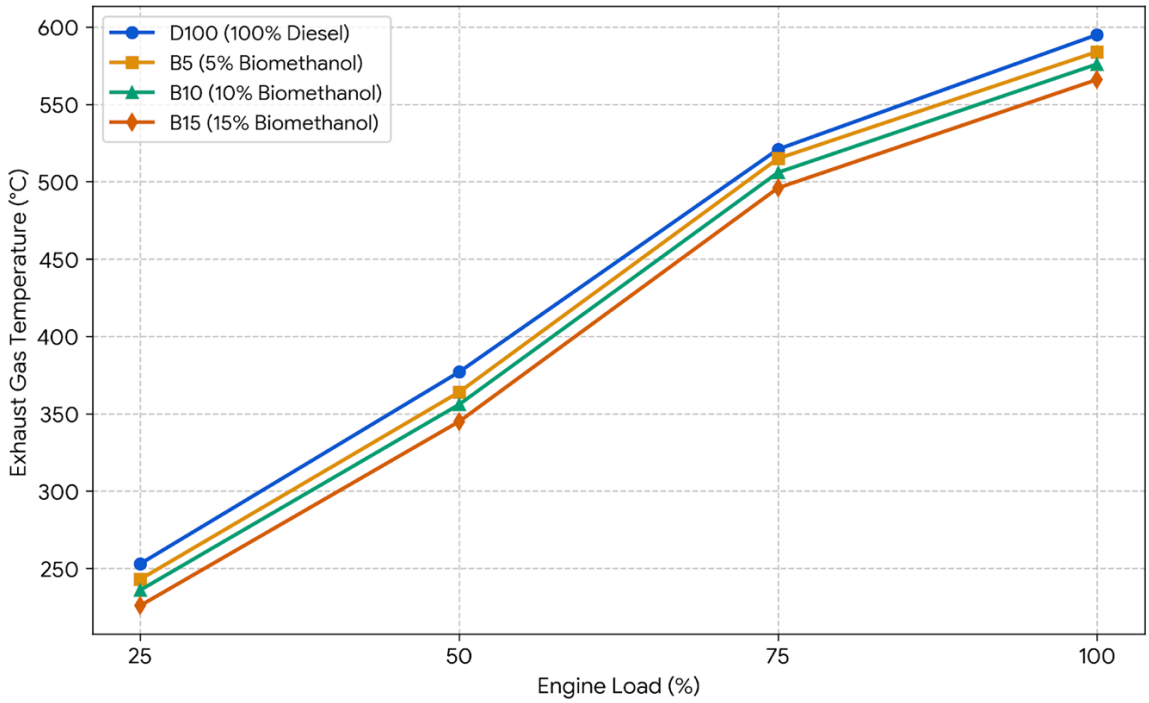


Figure 3. Exhaust gas temperature at different engine loads.

Carbon Monoxide (CO) Emissions

Carbon monoxide emissions are a product of incomplete combustion processes in which the carbon in the fuel cannot be fully oxidized. When the experimental data are examined (Figure 4), it is seen that CO emissions increase for all fuels as the amount of fuel injected into the cylinder increases due to the increase in engine load. However, the addition of biomethanol significantly improved CO emissions at all load stages compared to the reference diesel. The CO value, which was 0.09% vol for the D100 fuel under full load (100%) conditions, decreased to the level of 0.071% vol with the B15 blend.

The main reason for this decrease in CO emissions is the oxygen content of approximately 50% contained in the molecular structure of biomethanol (Uyumaz, 2020). This structural oxygen ensures more complete oxidation of carbon species even in locally rich mixture regions, which has also been reported in early methanol–diesel blend studies (He et al., 2003; Yılmaz et al., 2021). This situation, defined as the "oxygenated fuel effect" in the literature, accelerates the conversion of carbon atoms to carbon dioxide (CO2), suppressing CO formation (Yılmaz et al., 2021). In addition, the simple molecular structure of methanol and the absence of carbon-carbon bonds support this improvement by offering a cleaner combustion profile compared to diesel, which has complex hydrocarbon chains (Atmanlı et al., 2015).

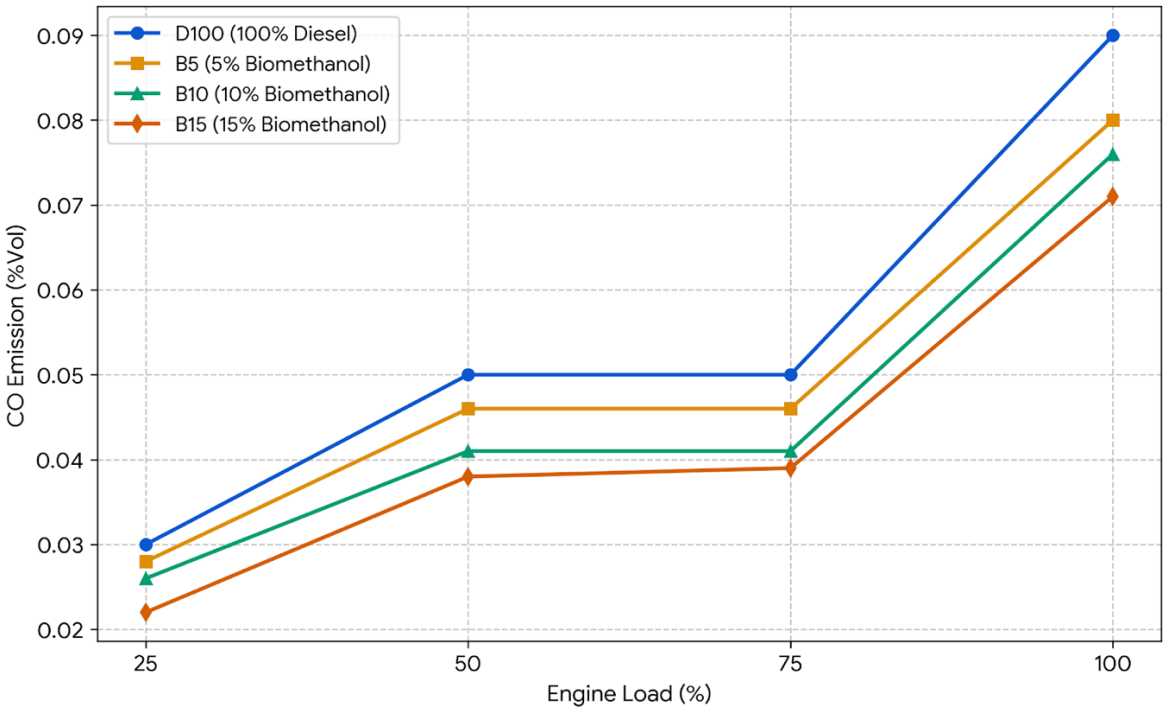


Figure 4. CO emission at different engine loads.

Nitrogen Oxide (NOx) Emissions

Nitrogen oxide emissions are primarily formed in internal combustion engines in accordance with the "Zeldovich mechanism" depending on high end-of-combustion temperatures and the oxygen concentration in the environment. Experimental results (Figure 5) show that in parallel with the in-cylinder temperatures increasing as the engine load increases, NOx emissions exhibit a sharp rise for all fuel types. However, the remarkable finding is that the addition of biomethanol increased NOx emissions at all load stages compared to the reference diesel. The value recorded as 2165 ppm for pure diesel (D100) under full load (100%) conditions reached the levels of 2282 ppm with 5% biomethanol (B5), 2355 ppm with 10% biomethanol (B10), and 2420 ppm with the use of 15% biomethanol (B15).

Despite the decrease observed in exhaust gas temperatures (EGT), this increase occurring in NOx emissions is attributed to several fundamental phenomena in the literature. Firstly, the high oxygen content in the molecular structure of biomethanol enriches the environment required for the oxidation of nitrogen during combustion, promoting its formation (Uyumaz, 2020). The second and more critical reason is the prolonged ignition delay as a result of the low cetane number of methanol (Öztürk & Canlı, 2022). During the prolonged ignition delay, more fuel-air mixture accumulates in the cylinder; this situation increases the amount of fuel burning suddenly in the pre-mixed combustion phase, leading to local temperature peaks (Yılmaz et al., 2021). Although the average exhaust temperature decreases, these local hot regions accelerate thermal NOx formation (Atmanlı et al., 2015). Consequently, the use of wheat straw-derived biomethanol in diesel engines improves soot and CO emissions while creating a "trade-off" situation in terms of NOx emissions.

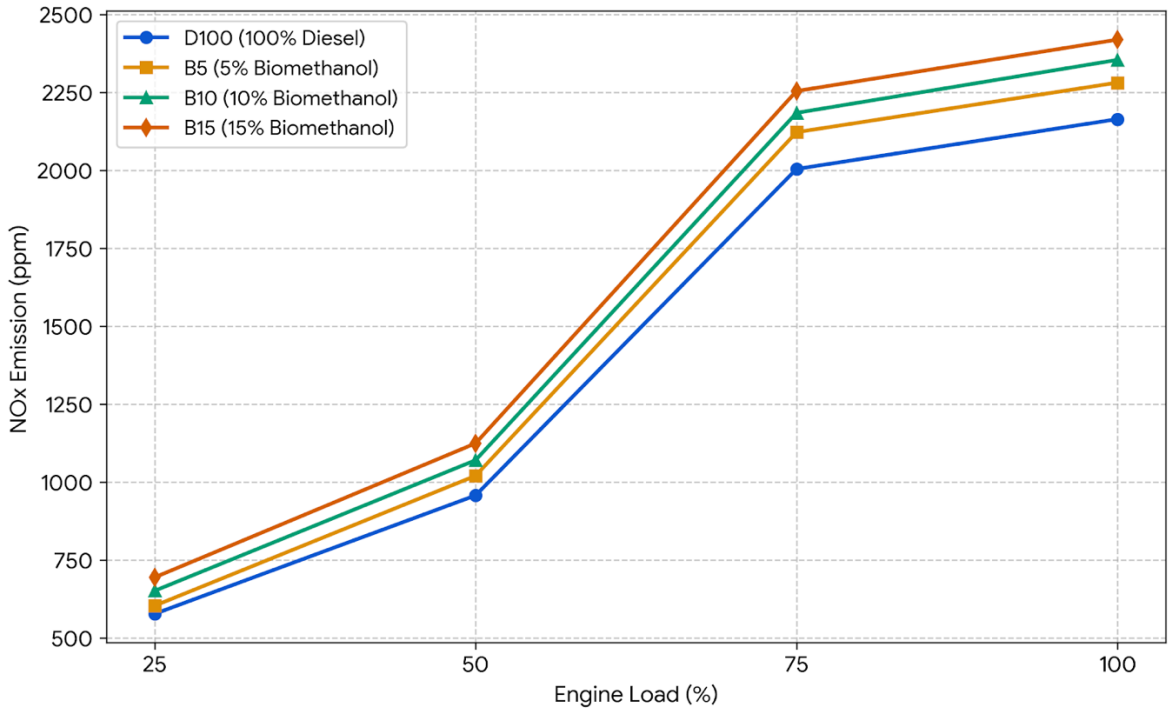


Figure 5. NOx emission at different engine loads.

Smoke Emissions

Smoke emissions occur in diesel engines as a result of the thermal decomposition (pyrolysis) of the fuel remaining oxygen-free under high temperatures, especially in fuel-rich mixture regions. Experimental results (Figure 6) show that smoke emissions increase for all fuel types depending on the increase in the amount of fuel sent into the cylinder along with the increase in engine load. However, the addition of biomethanol remarkably suppressed smoke formation under all operating conditions compared to the reference diesel. The smoke value, recorded as 10 BSN for pure diesel (D100) under full load (100%) conditions, decreased to 9.2 BSN with 5% biomethanol (B5), 8.5 BSN with 10% biomethanol (B10), and down to 7.5 BSN with the use of 15% biomethanol (B15).

This linear improvement observed in smoke emissions is fundamentally based on the high oxygen content (around 50%) in the molecular structure of biomethanol (Uyumaz, 2020). This structural oxygen eliminates the local oxygen deficiency around the fuel droplets, especially during the diffusion combustion phase, ensuring the complete oxidation of carbon atoms before they turn into soot particles (Öztürk & Canlı, 2022). In the literature, it is emphasized that short-chain and oxygenated fuels such as biomethanol prevent the formation of aromatic structures, which are soot precursors (Yılmaz et al., 2021). In addition, the lower carbon/hydrogen (C/H) ratio of methanol compared to diesel and the absence of carbon-carbon (C-C) bonds reinforce this environmental advantage by minimizing soot nucleation during combustion (Atmanlı et al., 2015). Consequently, blending wheat straw-derived biomethanol with diesel offers a highly effective solution in reducing smoke emissions, which is the most characteristic problem of diesel engines.

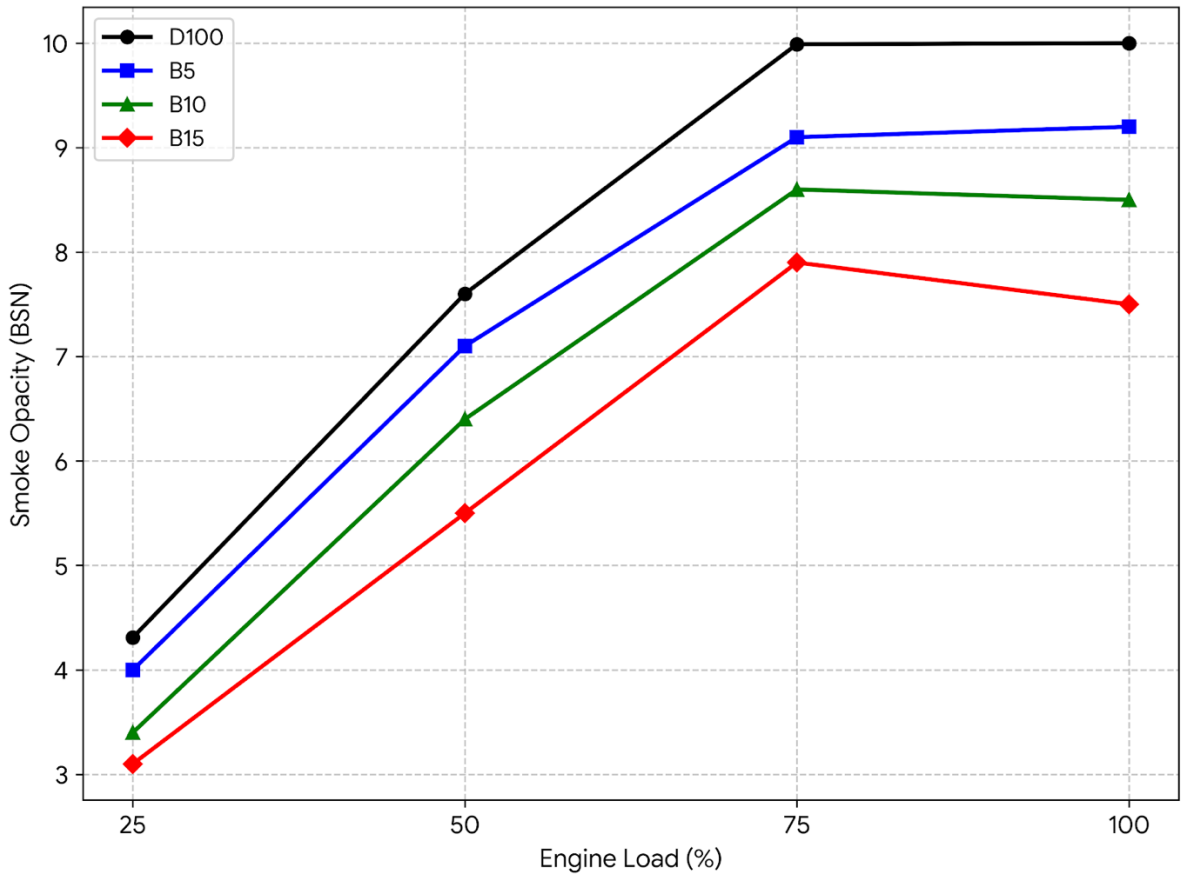


Figure 6. Smoke emission at different engine loads.

CONCLUSIONS

In this study, the potential of biomethanol produced from wheat straw — an agricultural waste — as an alternative fuel for diesel engines was experimentally investigated. Biomethanol was blended with pure diesel at volumetric ratios of 5%, 10%, and 15% (B5, B10, B15), and the effects of these blends on engine performance and exhaust emissions were evaluated on a single-cylinder diesel engine at four load stages (25%, 50%, 75%, and 100%). The main findings are summarized as follows:

Specific Fuel Consumption: Due to the lower heating value of biomethanol, SFC increased at all load stages with increasing blend ratio. Under full load conditions, SFC rose from 308 g/kWh (D100) to 346 g/kWh (B15), representing an increase of approximately 12.3%.

Exhaust Gas Temperature: The high latent heat of vaporization of biomethanol reduced in-cylinder temperatures, resulting in a decrease in exhaust gas temperature of 29 °C at full load — from 595 °C (D100) to 566 °C (B15).

CO and Smoke Emissions: The intrinsic oxygen content of biomethanol improved combustion quality, yielding the most favorable environmental outcomes in these parameters. At full load, smoke emissions were reduced by 25% and CO emissions by approximately 21% with the B15 blend compared to D100.

NOx Emissions: The addition of biomethanol increased NOx emissions at all load stages due to its low cetane number and associated ignition delay. At full load, NOx rose from 2165 ppm (D100) to 2420 ppm (B15).

Wheat straw-derived biomethanol demonstrates strategic potential for reducing particulate pollutants such as soot and CO while simultaneously valorizing agricultural waste streams. However, the concurrent increases in NOx emissions and fuel consumption indicate that injection timing optimization or exhaust after-treatment systems will be necessary when deploying such blends in practice.

Author Contribution Statement

The sole author contributed 100% to the conceptualization, literature review, design and execution of experiments, data collection, analysis of results, and the writing and revision of the manuscript.

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Artificial Intelligence (AI) Declaration

During the preparation of this manuscript, artificial intelligence (Gemini) was utilized solely to enhance the accuracy and readability of the English translation, to generate the schematic representation of the experimental setup, and to assist with reference formatting checks. The AI tool was not used in any way to generate the scientific content or analyze the data, and it is not credited as an author. The author assumes full scientific responsibility for the final content of the article.

Conflict of Interest Declaration

In accordance with the conflict of interest policy and my ethical obligation as a researcher, I hereby disclose that I previously served as the R&D Center Manager at Erin Motor A.Ş., where the experiments were conducted, and I currently provide professional consultancy services to the same company. I declare that this professional affiliation has in no way influenced the scientific objectivity of the study, the experimental results, or the analysis of the data. I have fully disclosed this situation to

the journal to prevent any potential misunderstandings. Other than this, the author declares no potential conflict of interest regarding the publication of this manuscript.

Ethical Declaration

This study does not involve clinical or experimental research on human or animal subjects; therefore, Ethics Committee Approval is not required. All processes in this study were conducted in strict accordance with the principles of the Pen Academic Publishing Research Ethics Policy.

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