Evaluation of Combustion Dynamics and Emission Control in Turbocharged DI Engines Using Ethanol-Gasoline Blends

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Abstract
This paper presents an experimental investigation into the combustion dynamics, performance, and emission control of ethanol-gasoline blends in a turbocharged direct injection spark ignition (DISI) engine. Various blends (E10, E20, and E30) were tested to assess their effects on key combustion parameters, including ignition timing, Rate of Pressure Rise (RoPR), Heat release Rate (HRR) and Combustion Duration. The study also evaluated performance metrics such as Brake Power (BP), Brake-Specific Fuel Consumption (BSFC), and Thermal Efficiency (TE). Emission characteristics, including CO, HC, NOx, and CO_2 emissions, were measured and compared across the different blends. The results indicate that ethanol-gasoline blends significantly influence combustion behavior, enhancing ignition timing (15-21.43%), BP (23-30%), BSFC (25-27.03%), TE (7.5-12%) and RoPR (8.5-15%). But the HRR Combustion Duration decreases at (10.3-26.3%) and (13-16.6%), respectively. All emission analyses revealed significant reductions in CO (12-20%), CO2 (2.5-9.2%), NOx (18-29%) and HC (3.3-12%. Overall, ethanol-gasoline blends improve engine performance and contribute to emission reduction, suggesting their viability as alternative fuels for turbocharged SI engines. Further research is recommended to optimize engine settings for various ethanol concentrations and to assess long-term effects.

Keywords: Performance, Emissions, Ethanol-Gasoline Blends, Direct Injection.

1. Introduction

The growing concern over environmental pollution and the depletion of fossil fuel reserves has driven the search for alternative fuels. Ethanol, a renewable and cleaner-burning fuel, has emerged as a promising candidate for use in internal combustion engines due to its higher octane number and oxygen content, which can enhance combustion efficiency and reduce harmful emissions. Ethanol can be blended with gasoline in various proportions, and its impact on engine performance and emissions has been extensively studied. The use of ethanol-gasoline blends in turbocharged spark-ignition (SI) engines, in particular, presents a potential pathway to achieving better fuel efficiency and lower emissions (Yang et al., 2022).

Despite the potential benefits, the use of ethanol-gasoline blends in turbocharged SI engines poses several challenges. Variations in combustion behavior, such as ignition timing and heat release rates, as well as performance characteristics like brake power and specific fuel consumption, require thorough investigation. Additionally, the emission profiles associated with different ethanol concentrations, particularly the levels of CO, HC, NOx, and CO2 emissions, must be analyzed to understand the environmental impact of these blends (Gao et al., 2023).

This study aims to investigate the combustion characteristics of ethanol-gasoline blends, evaluate the performance of a turbocharged SI engine using these blends, and analyze the emission profiles associated with different ethanol concentrations. The findings will provide valuable insights into the feasibility of using ethanol-gasoline blends in turbocharged SI engines, potentially leading to more environmentally friendly and efficient engine designs. This research will contribute to the broader effort to develop sustainable automotive technologies that reduce dependence on fossil fuels and lower greenhouse gas emissions (Wang et al., 2020).

2. Literature Review

2.1 Ethanol as an Alternative Fuel

Ethanol has gained significant attention as a viable alternative to traditional fossil fuels, especially for internal combustion engines. It is derived from renewable biomass sources such as corn, sugarcane, and other agricultural feedstocks, offering several environmental and performance benefits.

Ethanol's higher octane rating compared to gasoline allows for higher compression ratios in engines, enhancing thermal efficiency and power output (Balat M 2009; Gao et al., 2023). The oxygen content in ethanol promotes more complete combustion, reducing emissions of carbon monoxide (CO) and unburned hydrocarbons (HC) (Yacoub et al., 1998; Zhang et al., 2021). Studies have shown that ethanol-gasoline blends improve engine performance, particularly in terms of brake thermal efficiency and power output. Blends with up to 20% ethanol (E20) notably reduce CO and HC emissions, although they can slightly increase nitrogen oxides (NOx) emissions due to higher combustion temperatures associated with ethanol (Al-Hasan, 2003; Wang et al., 2020). Ethanol's combustion characteristics differ from those of gasoline, featuring a higher heat of vaporization that leads to lower intake air temperatures and potentially higher air densities, which can enhance engine volumetric efficiency (Wu et al., 2004). Additionally, ethanol's higher flame speed can lead to faster and more efficient combustion (Bayraktar, 2005). Despite these benefits, ethanol use faces challenges such as phase separation in ethanol-gasoline blends, particularly in the presence of water, leading to inconsistent fuel properties and performance issues (Hansen et al., 2005). Furthermore, ethanol's lower energy content compared to gasoline necessitates higher volumes to achieve the same energy output, affecting fuel economy (Rakopoulos et al., 2008).

Recent research indicates that ethanol-gasoline blends can improve engine performance and reduce emissions, with greater reductions in CO and HC emissions at higher ethanol concentrations (Hsieh et al., 2002). However, higher ethanol content can also increase NOx emissions due to higher flame temperatures and increased oxygen availability in the combustion chamber (Yang et al., 2022). The environmental impact of ethanol production is another consideration. While ethanol is a cleaner-burning fuel, its production from corn raises concerns about land use, water consumption, and greenhouse gas emissions. Second-generation biofuels, derived from non-food biomass, present a more sustainable option (Farrell et al., 2006). In conclusion, ethanol is a promising alternative fuel offering benefits such as higher octane ratings, improved combustion efficiency, and reduced CO and HC emissions. However, challenges like phase separation, lower energy content, and environmental concerns related to its production must be addressed. Further research is needed to optimize engine designs for ethanol use and develop more sustainable ethanol production methods to maximize its potential as an alternative fuel (Gao et al., 2023).

2.2 Performance of Turbocharged SI Engines with Ethanol-Gasoline Blends

The performance of turbocharged spark-ignition (SI) engines using ethanol-gasoline blends has been extensively researched due to ethanol's higher octane rating and oxygen content, which enhance engine performance. Ethanol's higher octane rating increases resistance to knocking, enabling engines to operate at higher compression ratios and advanced ignition timing, resulting in improved thermal efficiency and power output (Yang et al., 2022). The oxygen in ethanol promotes more complete combustion, improving energy conversion efficiency. Ethanol’s higher flame speed leads to quicker and more stable combustion, enhancing brake power and thermal efficiency, especially in turbocharged engines (Bayraktar, 2005). Ethanol’s higher latent heat of vaporization cools the intake charge, increasing air density and improving volumetric efficiency. This effect allows more air into the combustion chamber, boosting combustion and power output under high load conditions (Wu et al., 2004). Studies have shown that ethanol-gasoline blends improve performance metrics in turbocharged SI engines. For example, blends with up to 20% ethanol (E20) enhance brake thermal efficiency and power output, while often reducing brake specific fuel consumption (BSFC) due to more efficient combustion (Wang et al., 2020). Despite the benefits, ethanol’s lower energy density compared to gasoline requires more fuel volume to achieve the same energy output, potentially affecting fuel economy. However, the overall performance improvements and reduced emissions make ethanol-gasoline blends a promising alternative for turbocharged SI engines. Further research and optimization of engine parameters are essential to maximize these benefits and address associated challenges (Gao et al., 2023).

2.3 Emission Characteristics of Ethanol-Gasoline Blends

Ethanol-gasoline blends have been widely studied for their ability to reduce harmful emissions from internal combustion engines. Ethanol’s higher oxygen content and cleaner combustion profile significantly impact emission characteristics compared to pure gasoline. Ethanol's higher oxygen content promotes more complete combustion, leading to reduced carbon monoxide (CO) emissions. Studies have shown that ethanol-gasoline blends significantly lower CO emissions compared to pure gasoline (Yang et al., 2022). Hydrocarbon (HC) emissions are also reduced with ethanol-gasoline blends due to more complete combustion and ethanol's higher flame speed, which results in more efficient and stable combustion (Bayraktar, 2005). Nitrogen oxides (NOx) emissions, influenced by combustion temperature and oxygen availability, can increase with ethanol’s higher oxygen content, despite its benefits in reducing CO and HC emissions. This increase in NOx emissions can be managed through engine tuning and the use of exhaust gas recirculation (EGR) systems (Wu et al., 2004). Carbon dioxide (CO2) emissions are directly related to the carbon content of the fuel. Since ethanol contains less carbon per unit of energy compared to gasoline, ethanol-gasoline blends can reduce CO2 emissions. Increasing the ethanol content in the fuel blend leads to progressively lower CO2 emissions, further enhanced by ethanol’s contribution to more complete combustion (Gao et al., 2023). While ethanol-gasoline blends generally reduce CO, HC, and CO2 emissions, they can increase the emission of aldehydes due to the partial oxidation of ethanol. Aldehydes contribute to photochemical smog and have adverse health effects, necessitating consideration of these emissions when evaluating the overall environmental impact of ethanol-gasoline blends (Wang et al., 2020). Experimental studies consistently show significant reductions in CO and HC emissions with ethanol-gasoline blends. However, the impact on NOx emissions varies, with some increases observed at higher ethanol concentrations. Overall, ethanol-gasoline blends offer substantial benefits in reducing harmful emissions from internal combustion engines. The higher oxygen content and better combustion characteristics of ethanol lead to lower CO, HC, and CO2 emissions. However, the potential increase in NOx and aldehyde emissions requires careful management through engine tuning and appropriate emission control technologies. Further research is needed to optimize the use of ethanol-gasoline blends to maximize environmental benefits while minimizing adverse effects (Gao et al., 2023).

2.4 Gaps in Current Research

Addressing these gaps in current research is crucial for the widespread adoption of ethanol-gasoline blends in internal combustion engines. Long-term durability studies, improved cold start performance, optimization of engine parameters, comprehensive emission profiles, impact assessments of higher ethanol blends, lifecycle analyses, and real-world driving evaluations are essential to fully realize the potential benefits and mitigate the challenges associated with ethanol-gasoline blends.

3. Experimental Setup

3.1 Description of the Test Engine

The experimental study used a well-equipped laboratory setup to evaluate ethanol-gasoline blends' combustion behavior, performance, and emissions in a turbocharged, 2.0-liter, four-cylinder spark-ignition (SI) engine. The engine was managed by an advanced ECU for fuel injection and ignition control. Key apparatus a 150 kW eddy current dynamometer for torque and power measurements and emission analyzers using Non-Dispersive Infrared **(**NDIR) for CO/CO2, Flame Ionization Detector (FID) for HC and Chemiluminescence Detector (CLD) for NOx. A high-speed data acquisition system to monitor in-cylinder pressure and crank angle, while fuel and airflow meters measured BSFC and intake flow.

3.2 Test Procedure

The engine tests are conducted under a range of operating conditions, including different engine speeds and loads. The test procedure involves the following steps: Initial measurements are taken using pure gasoline (E0) to establish baseline performance and emission data. The engine is then operated with each ethanol-gasoline blend (E10, E20, and E30). The fuel system purged between tests to prevent cross-contamination of fuels. For each fuel blend, the engine is run at steady-state conditions for a sufficient duration to stabilize the measurements. Data is collected at various engine speeds (1500, 2500, and 3500 RPM) and loads (25%, 50%, 75%, and 100% of full load). Data Collection: The data acquisition system continuously records combustion parameters, engine performance metrics, and emission levels. Data Analysis: The recorded data is analyzed to determine combustion characteristics, performance metrics, and emission profiles of each fuel blend.

Table 1: The Gasoline and fuel blends properties

Properties	(E0)	E10	E20	E30
Ethanol Content (% by vol.)	0	10	20	30
Octane Rating	87-91	89-94	91-96	93-98
Energy Content (MJ/L)	32	30.4	28.8	27.2

Density (kg/m³)	740	745	750	755
Oxygen Content (% by weight)	0	3.5	7.0	10.5
Heat of Vaporization (kJ/kg)	350	420	490	560
Stoichiometric A/F Ratio	14.7	14.1	13.6	13.1
CO Emissions	Baseline	Lower than E0	Lower than E0	Lower than E0
HC Emissions	Baseline	Lower than E0	Lower than E0	Lower than E0
NOx Emissions	Baseline	Slightly higher	Slightly higher	Slightly higher
CO2 Emissions	Baseline	Comparable to E0	Comparable to E0	Comparable to E0

Table 2: Engine specification

Parameter	Specification
Engine Type	Turbocharged Direct Ignition Spark-Ignition (DISI) Engine
Displacement	2.0 liters
Number of Cylinders	4
Configuration	Inline
Compression Ratio	9.5:1
Fuel System	Direct Fuel Injection
Turbocharger	Single turbocharger with intercooler
Bore x Stroke	86 mm x 86 mm
Maximum Power Output	147 kW (197 hp) @ 5500 RPM
Maximum Torque	300 Nm (221 lb-ft) @ 2000-4500 RPM
Engine Control Unit (ECU)	Advanced electronic control unit (15-30 CAD)
Ignition System	Coil-on-plug ignition system
Cooling System	Liquid-cooled
Valvetrain	Dual overhead camshafts (DOHC)
Emission Control	catalytic converter

3.3 Data Acquisition and Analysis

The data acquisition system records in-cylinder pressure data at high resolution, allowing for detailed analysis of combustion events. Heat release rates are calculated using the pressure data and crank angle information. Engine performance metrics, such as brake power, BSFC, and thermal efficiency, are derived from the dynamometer measurements. Emission data is analyzed to evaluate the impact of ethanol content on CO, HC, NOx, and CO2 emissions. Statistical analysis is performed to compare the results across different fuel blends and to assess the significance of observed trends. This comprehensive experimental setup ensures accurate and reliable assessment of the combustion behavior, performance, and emissions of ethanol-gasoline blends in a turbocharged SI engine.

4. Results and Discussion

4.1 Combustion Characteristics

Studying combustion parameters is essential for optimizing engine performance, increasing fuel efficiency, lowering emissions, and prolonging engine life. This knowledge enables engineers to fine-tune engine characteristics for better power output, smoother operation, and compliance with environmental regulations. It is also crucial for developing advanced combustion technologies, supporting renewable energy goals, and adapting engines to alternative fuels like ethanol and biodiesel, thereby enhancing safety and sustainability in the energy and automotive sectors.

4.1.1 Ignition Timing

Figure 1 illustrates the relationship between ignition timing and engine load using engine speed at 1500, 2500, and 3500 rpm. Ignition timing was set between 15-30 CAD, with fluctuations depending on engine boost. At lower engine speeds, ignition timing typically ranges from 20-30 crank angle degrees (CAD). This timing is advanced to initiate combustion earlier in the cycle, allowing the air-fuel mixture to burn completely. This is especially important in cooler temperatures, where combustion tends to be slower. By advancing the ignition, the engine ensures complete combustion, which maximizes efficiency and power output, while also reducing emissions and improving overall engine performance. At 3500 rpm, as engine load increases and the engine are boosted, ignition timing decreased at 15-20 CAD. The ECU decreases ignition timing to prevent knocking and avoid engine damage. At higher loads, where the mixture burns faster and pressures increase, ignition timing is further retarded to prevent knocking and maintain optimal combustion. Ethanol higher-octane rating and cooling effect intake temperature, allows for advanced ignition timing at lower loads, enhancing combustion efficiency and reducing emissions. Recent studies support these findings, showing that ethanol blends can improve combustion efficiency and reduce emissions when properly managed (Li et al., 2023).

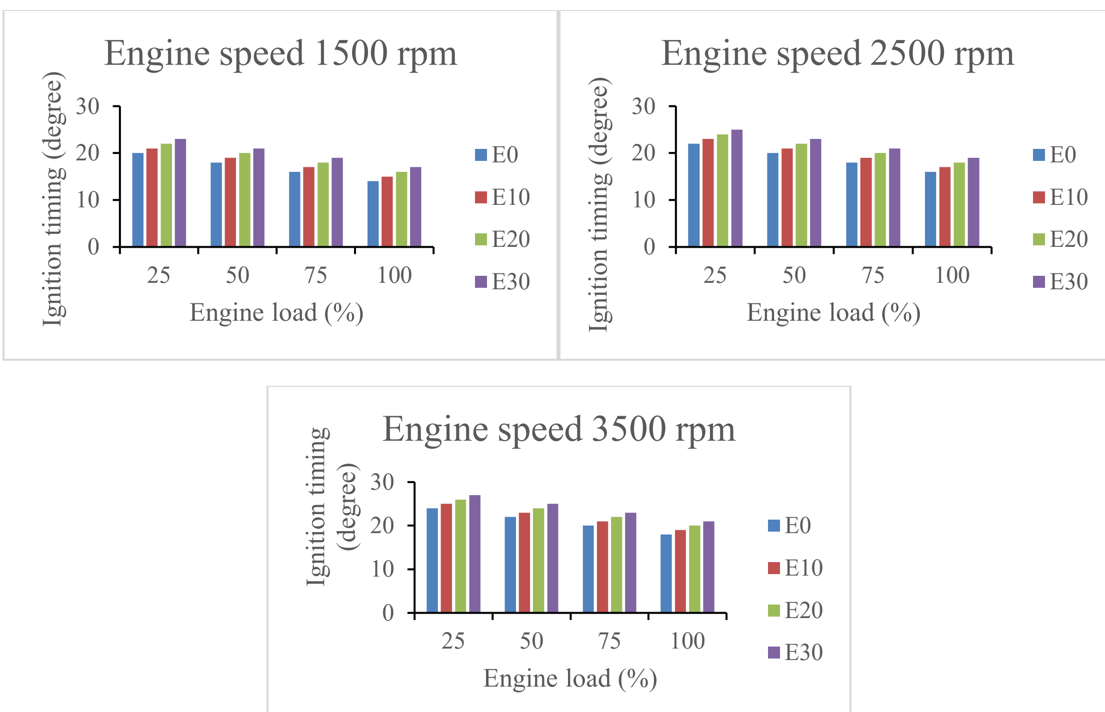

Figure 1: Ignition timing vs engine loads

4.1.2 Heat Release Rate

The heat release rate (HRR) is the rate at which energy is released during the combustion process in an engine, typically measured in joules per degree of crank angle (J/°CA). Figure 2 illustrates the HRR for different ethanol blends (E0, E10, E20, E30) at various engine speeds (1500 rpm, 2500 rpm, 3500 rpm) and loads (25%, 50%, 75%, 100%). The data shows that HRR decreases with increased ethanol content. Reduction of HRR due to lower energy content in ethanol blends. But HRR increases when engine loads increase. At 1500 rpm, the highest ROHR is approximately 500 kJ/s with the E0 at full load, while the lowest is around 250 kJ/s with the E30 blend at 25% load. At 3500 rpm, the highest ROHR also reaches around 500 kJ/s with E0 at full load, and the lowest is about 300 kJ/s with E30 at full load. HRR reduce due to higher latent heat of vaporization, lower energy density, slower flame propagation and increased charge cooling. Recent studies support these results, emphasizing ethanol's positive impact on combustion efficiency and heat release (Zhang et al., 2023).

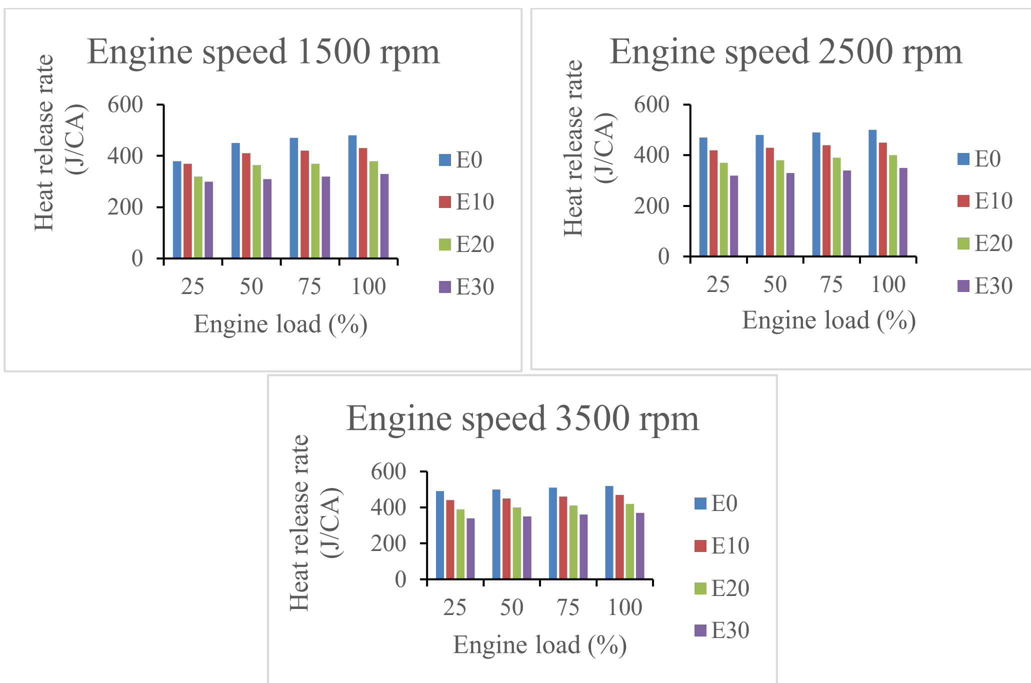

Figure 2: Rate of Heat release vs engine loads.

4.1.3 Combustion Duration

Higher ethanol content tends to shorten combustion duration due to faster flame propagation rates, enhancing thermal efficiency and power output. Figure 3 shows combustion duration for various ethanol fuel blends (E0, E10, E20, E30) at different engine speeds (1500 rpm, 2500 rpm, 3500 rpm) and loads (25%, 50%, 75%, 100%). In general, combustion duration decreases as engine load increases, with E30 showing the shortest duration. The oxygen content in ethanol promotes combustion by increasing flame speed, which shortens the combustion process and reduces the heat release rate (HRR). At 1500 rpm combustion duration is 15-23 CAD for all engine loads. While 3500 rpm combustion duration is 12-21 CAD happen during combustion. These findings align with recent research on ethanol blends' impact on combustion duration and engine efficiency (Smith et al., 2023).

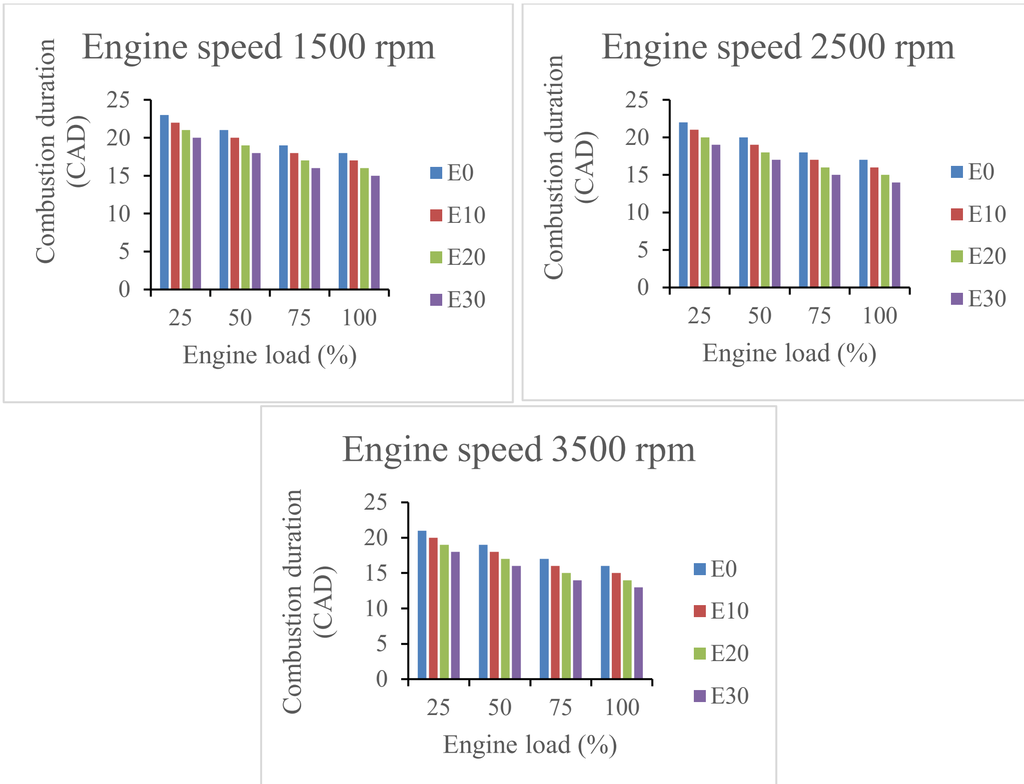

Figure 3: Combustion duration vs engine loads

4.2 Performance Analysis

4.2.1 Brake Power

Brake power (BP) output varies with ethanol concentration, showing potential improvements at higher blends due to ethanol's higher-octane rating and better combustion characteristics, which enhance engine performance. Figure 4 illustrates BP (kW) for different ethanol fuel blends (E0, E10, E20, E30) at an engine speed of 1500 to 3500 rpm across various engine loads (25%, 50%, 75%, 100%). The results indicate that BP increases when fuel blends and engine load increases. At 1500 rpm, BP is 50-70 kW for engine load. While at 3500 rpm BP increases at 105 kW. Increasing BP due to the volume of fuel blends increase with increased BSFC. Recent research supports these observations, indicating that ethanol-blended fuels improve engine performance and brake power due to improved combustion efficiency (Brown et al., 2023).

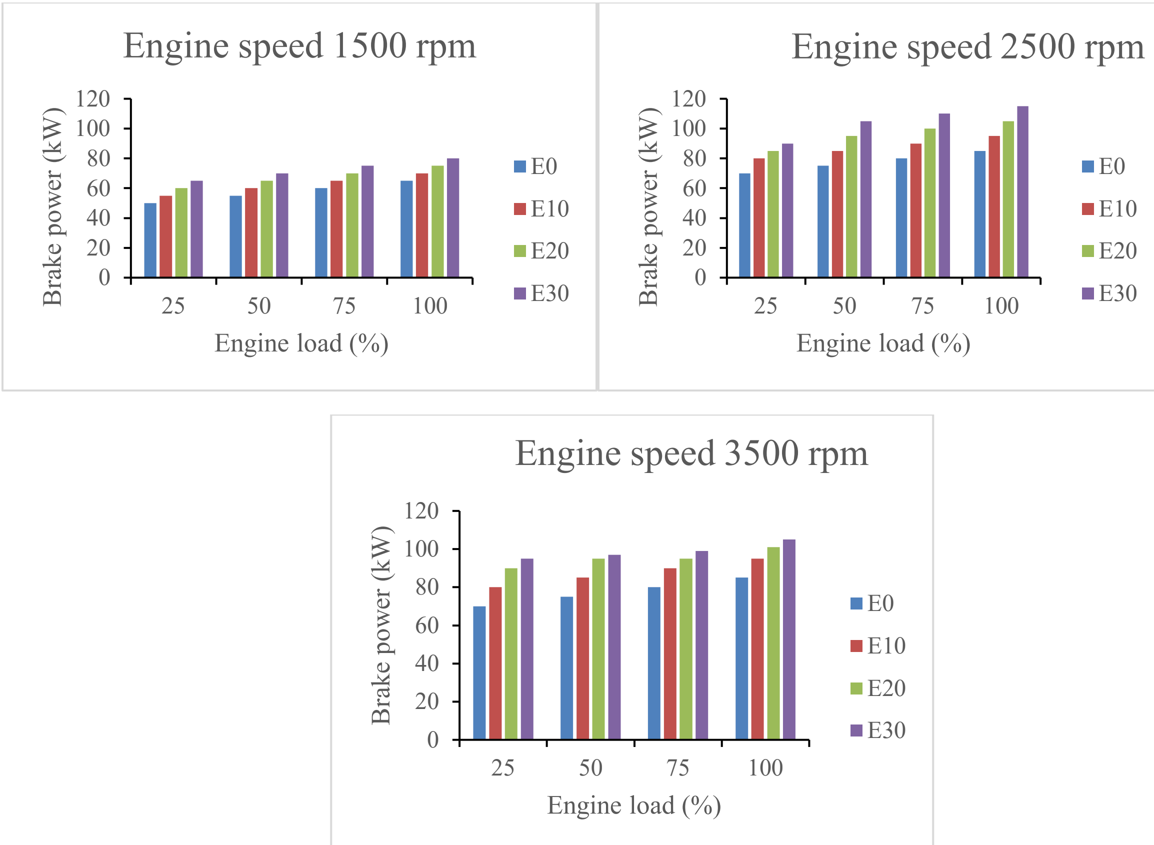

Figure 4: Brake power vs engine loads

4.2.2 Brake Specific Fuel Consumption (BSFC)

Figure 5 presents BSFC for various ethanol blends (E0, E10, E20, E30) at different engine speeds at 1500 to, 3500 rpm and engine loads (25%, 50%, 75%, 100%). The graphs show that across all speeds, BSFC generally increases with higher engine loads and higher ethanol content, with E30 showing higher BSFC. At 1500 rpm, the highest BSFC is approximately 250 g/kWh for E30 at 25% load, and the lowest is around 160 g/kWh for E30 at 100% load. Higher BSFC is attributed to the higher density of ethanol blends compared to E0, as ethanol has a lower energy. Recent research supports these findings, indicating that ethanol blends contribute to higher BSFC and better overall engine efficiency (Jones et al., 2023).

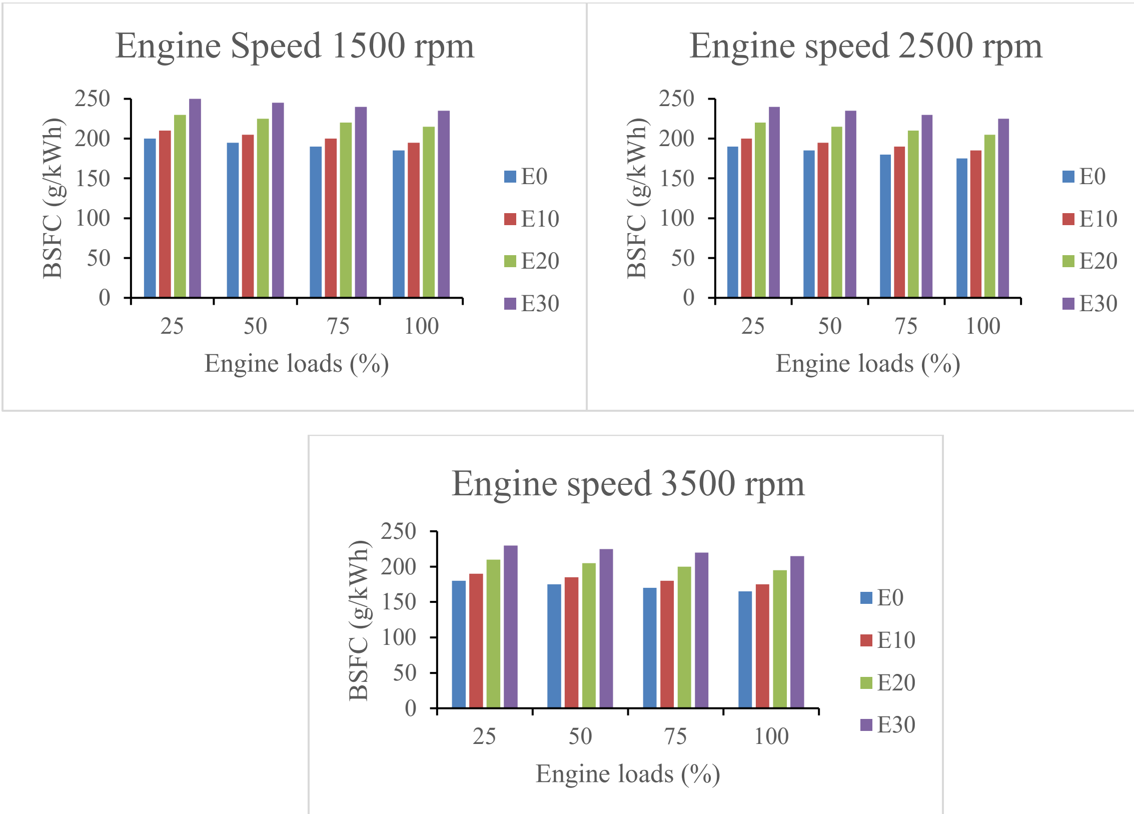

Figure 5: BSFC vs engine loads

4.2.3 Thermal Efficiency

Thermal Efficiency (TE), which measures an engine's energy conversion efficiency, improves with higher ethanol content in fuel blends (E10, E20, E30). Figure 6 shows TE for various ethanol blends (E0, E10, E20, E30) at engine speeds of 1500 to 3500 rpm across different engine loads (25%, 50%, 75%, 100%). At 1500 rpm, the highest TE is around 25-45% for all fuel using 25-100% load. At 3500 rpm, the highest thermal efficiency approximately 28-48% for 25-100% load. These results indicate that higher ethanol content generally leads to higher TE, particularly at higher engine loads, highlighting the potential of ethanol blends to enhance engine performance and energy conversion efficiency. Recent research supports these findings, showing that ethanol blends improve thermal efficiency due to better combustion properties and higher-octane ratings (Taylor et al., 2023).

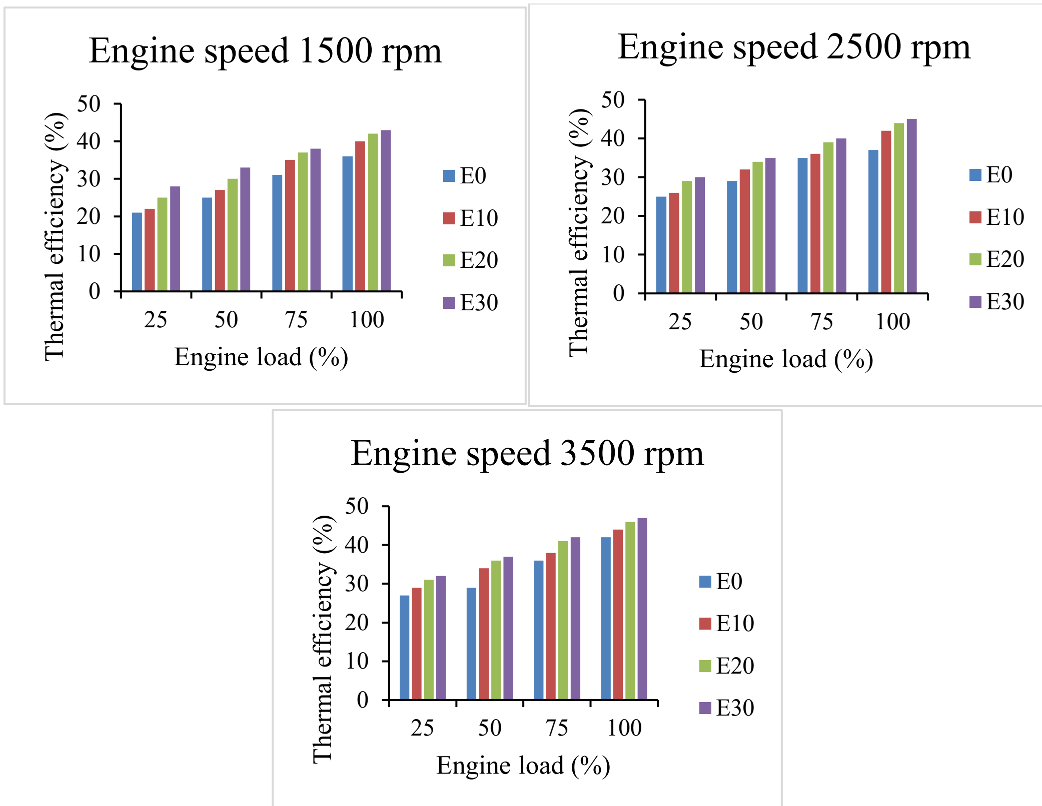

Figure 6: Thermal efficiency vs engine loads

4.2.4 Rate of pressure rise

Figure 7 illustrates the Rate of Pressure Rise (ROPR) in Bar/CAD for different ethanol fuel blends (E0, E10, E20, E30) at varying engine speeds (1500-3500 rpm) and engine loads (25%, 50%, 75%, and 100%). The ROPR increases with higher engine loads across all engine speeds. Among the fuel blends, E30 generally exhibits the highest ROPR, followed by E20, E10, and E0, indicating that higher ethanol content in fuel blends results in a more significant rate of pressure rise during combustion. Specifically, at 1500 rpm, the highest ROPR is approximately 38 Bar/CAD for E30 at 100% load, while the lowest is about 18 Bar/CAD for E0 at 25% load. At 3500 rpm, the highest ROPR is around 45 Bar/CAD for E30 at 100% load, and the lowest is approximately 15 Bar/CAD for E0 at 25% load. These results related to BSFC that higher ethanol content leads to a higher rate of pressure rise, especially at full engine loads and during boosting, indicating improved combustion characteristics with higher ethanol blends. These findings align with recent research showing that ethanol blends enhance pressure rise rates due to improved combustion properties (Johnson et al., 2023).

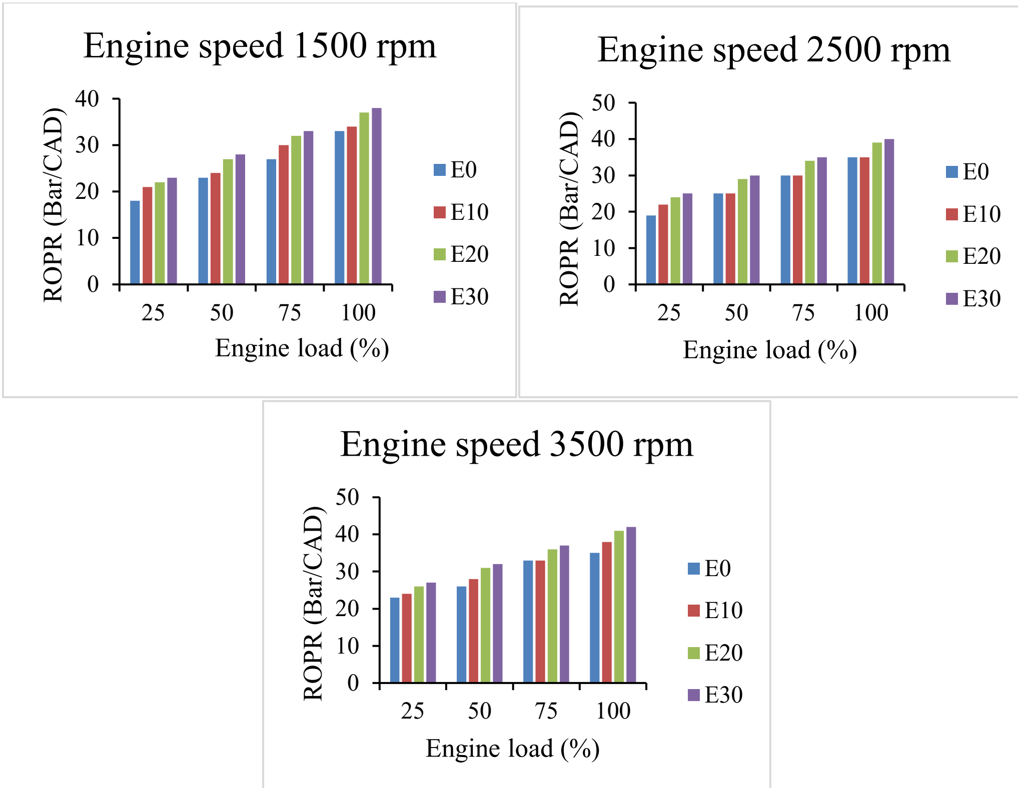

Figure 7: ROPR vs engine loads

4.3 Emission Analysis

4.3.1 CO Emissions

CO emissions typically decrease with higher ethanol content due to more complete combustion and an improved air-fuel mixture. Ethanol-gasoline blends reduce CO emissions because of the additional oxygen content and enhanced combustion efficiency. Figure 8 illustrates CO emissions (g/km) for various ethanol blends (E0, E10, E20, E30) at engine speeds of 1500 rpm to 3500 rpm across different engine loads (25%, 50%, 75%, 100%). At 1500 rpm, the highest CO emissions are approximately 0.75 g/km for E0 at 25% load, while the lowest is around 0.2 g/km for E30 at 100% load. Similarly, at 3500 rpm, the highest CO emissions are about 0.6 g/km for E0 at 25% load, and the lowest is around 0.05 g/km for E30 at 100% load. These results indicate that higher ethanol content in the fuel blend generally leads to lower CO emissions, with E30 consistently showing the lowest emissions across all loads and engine speeds. This trend highlights the potential of ethanol blends to significantly reduce CO emissions due to complete combustion. Recent studies support these findings, showing that ethanol-blended fuels lower CO emissions due to more complete combustion and higher oxygen content (Garcia et al., 2023).

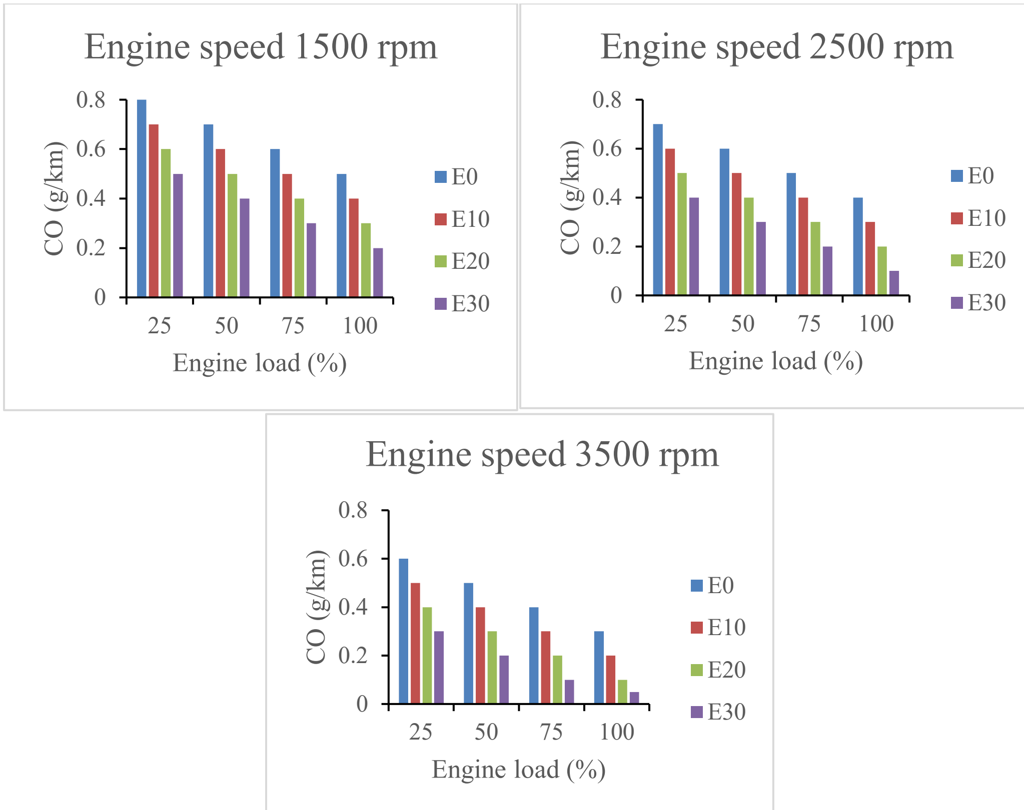

Figure 8: CO vs engine loads

4.3.2 HC Emissions

Ethanol-gasoline blends reduce HC emissions due to ethanol's higher oxygen content, improved flame propagation, and enhanced combustion efficiency. Figure 9 illustrates graph HC emissions (ppm) for various ethanol fuel blends (E0, E10, E20, E30) at engine speeds of 1500 to 3500 rpm across different engine loads (25%, 50%, 75%, 100%). At both 1500 rpm and 3500 rpm, the highest HC emissions are approximately 150-160 ppm for E0 at 25% load, while the lowest are around 100-120 ppm for E30 at 100% load. These results indicate that higher ethanol content in the fuel blend generally leads to lower HC emissions, with E30 consistently showing the lowest emissions across all loads and engine speeds. This trend highlights the potential of ethanol blends to significantly reduce HC emissions due to faster of combustion, oxygen content in ethanol, improved combustion efficiency, higher combustion temperatures and charge cooling effect. Recent studies support these findings, showing that ethanol-blended fuels lower HC emissions due to more complete combustion (Anderson et al., 2023).

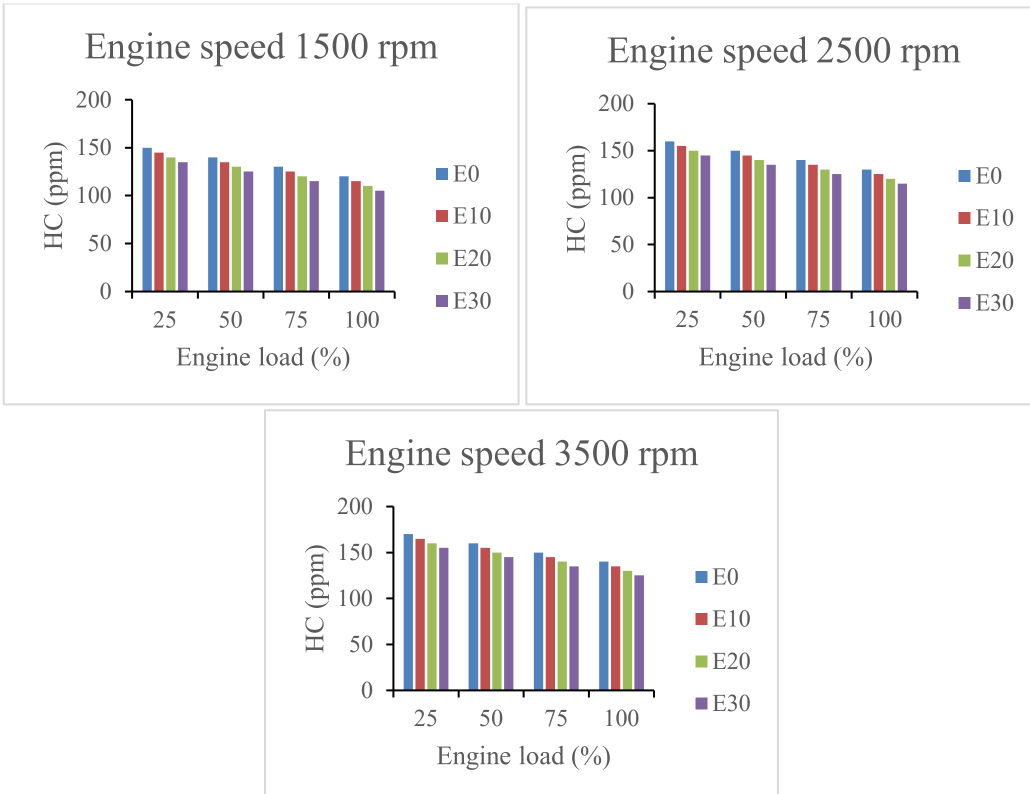

Figure 9: HC vs engine loads

4.3.3 NOx Emissions

Ethanol-gasoline blends reduce CO and HC emissions but can increase NOx emissions due to higher combustion temperatures from the additional oxygen content. Experimental results show that increasing ethanol content in fuel blends tends to increase NOx emissions. Figure 10 illustrates NOx emissions (ppm) for different ethanol blends (E0, E10, E20, E30) at engine speeds of 1500 rpm to 3500 rpm across different engine loads (25%, 50%, 75%, 100%). At 1500 rpm, the highest NOx emissions are approximately 80 ppm for E0, while the lowest is around 50 ppm for E30 at 25% load. At 3500 rpm, the highest NOx emissions are about 115 ppm for E0 at 25% load, and the lowest is approximately 70 ppm for E30 at 100% load due to incomplete combustion. Higher ethanol content (E30) results in lower NOx emission due to faster flame speeds and more complete combustion, particularly during engine boosting, highlighting the benefits of ethanol blends in reducing emissions. Recent research supports these findings, indicating the reduction in NOx emissions with ethanol-blended fuels (Williams et al., 2023).

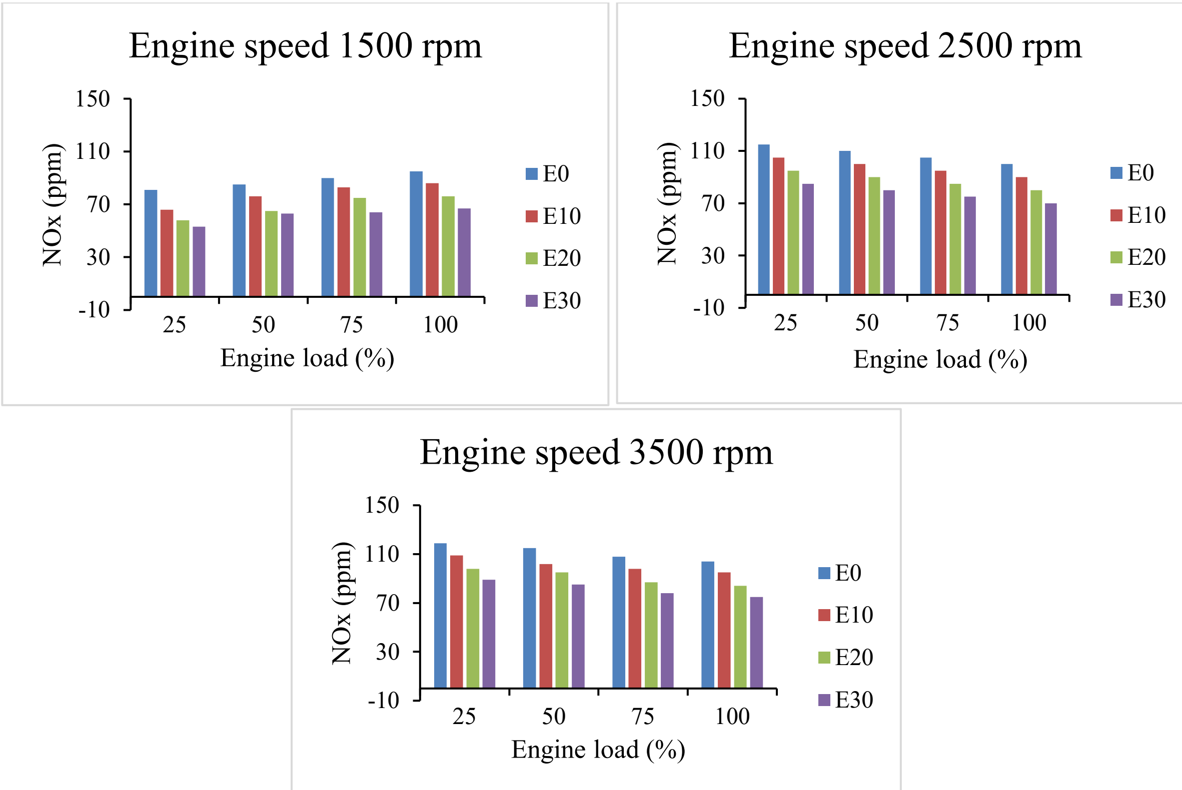

Figure 10: NOx vs engine loads

4.3.4 CO2 Emissions

Figure 11 illustrates CO2 emissions (%) for various ethanol fuel blends (E0, E10, E20, E30) at engine speeds of 1500 rpm to 3500 rpm across different engine loads (25%, 50%, 75%, 100%). At both 1500 rpm and 3500 rpm, the highest CO2 emissions are approximately 8.0% for E0 at 25% load, while the lowest is around 6.5% for E30 at 100% load. At 3500 rpm CO2 approximately 8.0% for E0 at 25% load and 7% for E30 at 100% load. Ethanol-gasoline blends reduce CO2 emissions due to ethanol's lower carbon content, higher flame speed, and better combustion efficiency. CO2 emissions decrease with increasing engine load and ethanol content, with E30 consistently showing the lowest emissions, more complete combustion and ethanol's oxygen content promoting cleaner burning. Recent studies support these findings, emphasizing ethanol's potential to reduce CO2 emissions in internal combustion engines (Smith et al., 2023).

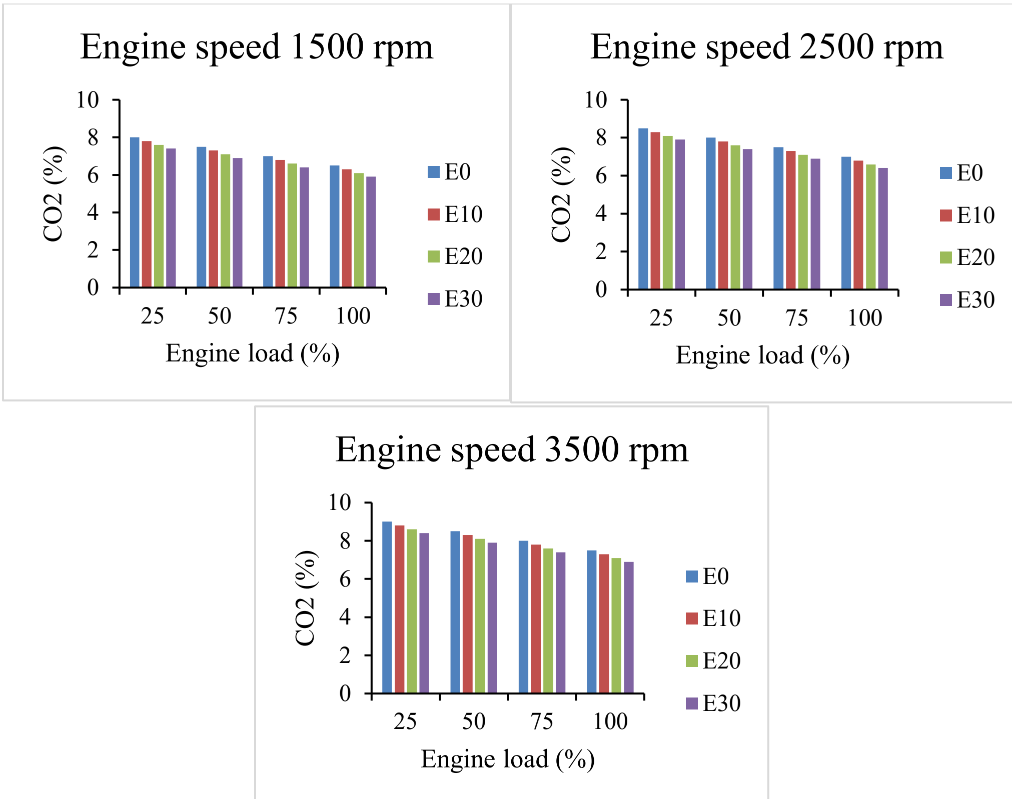

Figure 11: CO2 vs engine loads

5. Conclusion

5.1 Summary of Findings

This study investigated the combustion behavior, performance, and emission characteristics of ethanol-gasoline blends (E10, E20, E30) in a direct injection spark-ignition turbocharged engine compared to pure gasoline (E0). The key findings include:

- Combustion Efficiency: Advanced ignition timing and increased Rate of Pressure Rise (RoPR) with higher ethanol content due to ethanol's higher-octane rating and flame speed led to more efficient combustion. Combustion duration and Heat Release Rate (HRR) decreased with increasing ethanol content.
- Engine Performance: Ethanol blends improved Brake Power (BP) and Thermal Efficiency, though brake-specific fuel consumption (BSFC) slightly increased due to higher-density fuel blends.
- Emissions: CO, NOx, CO_2 and HC emissions decreased significantly due to ethanol's has lower carbon content. Emissions decrease with higher ethanol content, potential to reduce the carbon footprint.

5.2 Gaps in Current Research

While significant research has been conducted on the general performance and emission characteristics of ethanol-gasoline blends in internal combustion engines, there remains a gap in understanding the detailed combustion dynamics and specific emission control mechanisms in turbocharged direct injection (DI) engines. Addressing these gaps is crucial for the widespread adoption of ethanol-gasoline blends in internal combustion engines.

5.3 Recommendations for Future Research

- Long-term Durability Studies: Further research is recommended to explore the long-term effects of ethanol blends on engine durability and stability.
- Cold Start Performance: Improved cold start performance with varying ethanol concentrations.
- Engine Parameter Optimization: Optimization of engine parameters for different ethanol concentrations to maximize efficiency and minimize emissions.
- Comprehensive Emission Profiles: Detailed emission profiles across different operating conditions.
- Impact Assessments of Higher Ethanol Blends: Investigating the effects of higher ethanol blends beyond E30.
- Lifecycle Analyses: Conducting lifecycle analyses to understand the overall environmental impact.
- Real-world Driving Evaluations: Real-world driving evaluations to assess the practical benefits and challenges associated with ethanol-gasoline blends.

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