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Numerical Investigation of Ethanol-Enriched Diesel and Biodiesel Fuels in a Diesel Engine

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ABSTRACT

This study explores the effects of ethanol blending on the performance and emissions of a compression ignition (CI) engine using both diesel and biodiesel as base fuels. Motivated by increasing environmental concerns regarding pollutant emissions from conventional diesel engines, ethanol was introduced as an oxygenated additive to improve combustion characteristics and reduce the formation of harmful exhaust emissions. Ethanol's high oxygen content promotes more complete combustion, potentially lowering carbon-based emissions such as carbon monoxide (CO), particulate matter (PM), and unburned hydrocarbons. In this study, performance and emission parameters were simulated using Diesel-RK software at various engine speeds of 1500, 2000, and 2200 rpm, with ethanol blending ratios of 10%, 20%, 35%, and 50%. The simulations measured specific fuel consumption (SFC), brake mean effective pressure (BMEP), Sauter mean diameter (SMD) of fuel droplets, and emissions including carbon dioxide (CO_2), nitrogen oxides (NO_x), PM, and smoke opacity. The results indicated that a 35% ethanol blend delivered the most favorable balance between performance enhancement and emission reduction. Notably, SFC was reduced by up to 5.42% and 4.81% at 1500 and 2200 rpm, respectively. Furthermore, CO_2 emissions dropped significantly, by 9.23% and 9.11% at 2000 and 2200 rpm for biodiesel-ethanol blends. Additionally, PM and smoke showed substantial decreases. These findings suggest that ethanol blends in the range of 20% to 35% are optimal for enhancing the sustainability and environmental compatibility of CI engines by reducing emissions while maintaining engine performance.

Keywords: *CI engine, diesel-RK simulation, emission reduction, engine performance, ethanol blending.*

I. Introduction

Diesel engines are widely utilized across transportation, industrial, and power generation sectors due to their high energy efficiency and durability [1]. However, they are also major contributors to environmental pollution, particularly in the form of carbon dioxide (CO_2), nitrogen oxides (NO_x), particulate matter (PM), and unburned hydrocarbons [2]. These emissions have prompted significant concern regarding their contribution to air quality degradation and climate change. Globally, diesel vehicles are responsible for up to 74.6% of NOx emissions from road transportation and contribute approximately 49.1% of PM emissions from on-road transport globally [3]. In urban areas, particularly in developing countries, diesel sources are responsible for 31.7 $\mu g/m^3$ of PM 2.5 concentrations during peak traffic hours [4]. In European cities, diesel passenger vehicles account for up to 29% of NOx emissions from cars, despite being less than half the fleet [5].

To address these challenges, various strategies have been implemented to improve the quality of diesel fuel and reduce its environmental impact. These include blending diesel

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with biodiesel that has low and high boiling point fuel can improve the quality of fuel [6–8], utilizing water-emulsified diesel fuels that can reduce NOx emissions [9],[10], and incorporating oxygenated additives such as ethanol that can decrease the emissions in diesel engines [11],[12]. Ethanol, in particular, has received increasing attention due to its high oxygen content, renewable nature, and potential to reduce harmful emissions

Several studies have highlighted the benefits of ethanol blending. Wang *et al.* [13] demonstrated that blending 20% ethanol with diesel improved thermal efficiency by 3.63% and increased cylinder pressure slightly. Emmanuelle *et al.* [14] evaluated ethanol blends under various load and speed conditions and found that while power and torque slightly decreased, emissions showed significant reductions. Similarly, Benea [15] observed increased power and torque with ethanol blends up to 8%. Chaichan *et al.* [16] reported that combining ethanol with methanol and EGR technology reduced NO_x and PM emissions effectively. Klinkaew *et al.* [17] also found that crude castor oil blended with diesel-ethanol mixtures could lower NO_x and smoke emissions at low loads.

Despite these promising findings, blending ethanol with diesel or biodiesel poses technical challenges due to differences in fuel properties such as viscosity, volatility, and cetane number. For example, adding 10–20 vol% ethanol to diesel can raise the peak pressure in the cylinder by about 25% and the temperature in the cylinder by up to 60 °C. It can also delay ignition by almost 1° crank angle. These effects are mostly due to ethanol's low cetane number and calorific value, even though it helps with spray atomization and makes the fuel more volatile [18].

This study aims to analyze the effects of ethanol blending on CI engine performance and emissions through simulation using Diesel-RK software. Diesel-RK was chosen because of its advantages in predicting combustion in diesel engines using various fuels. In this study, a comparative assessment was conducted for diesel-fuel-ethanol (DFE) and biodiesel-ethanol (BDE) blends at varying engine speeds (1500, 2000, and 2200 rpm) and ethanol concentrations (10%, 20%, 35%, and 50%). The parameters analyzed include SFC, BMEP, SMD, and exhaust emissions (CO_2, NO_x, PM, and opacity). This work contributes to identifying optimal ethanol blending ratios that balance emission reduction and engine performance.

II. Material and Methods

The simulation in this study was conducted using Diesel-RK, an open source from Bauman Moscow State Technical University. A thermodynamic and combustion kinetics simulation tool specifically developed for compression ignition (CI) engines [19]. Diesel-RK is capable of modeling various engine performance and emission parameters based on input engine configurations and fuel properties. The software also provides visualization of fuel spray, ignition delay prediction, and dual-fuel combustion simulation [20].

1. Simulation Procedures

Before the simulation is started, some data should be prepared in order to complement the calculation in the diesel RK. The simulation procedure using Diesel-RK consists of the following steps:

1. Project initialization: A new simulation project was created based on the test engine specifications.

2. Engine system selection: The engine was configured as a four-stroke, direct-injection, supercharged CI engine.
3. Input of engine parameters: Engine specifications (see Table 1) including bore, stroke, compression ratio, injection system, injection pressure, and engine speed, were entered.
4. Fuel property definition: Physical and chemical properties of the fuels (density, viscosity, LHV, cetane number, etc.) were input based on experimental values (see Table 2).
5. Operating regime setup: Simulations were run at three different engine speeds: 1500, 2000, and 2200 rpm. These conditions were chosen because they are realistic and can provide insight into the emission characteristics and engine response under practical operating conditions.
6. Output analysis: The simulation results were analyzed in terms of specific fuel consumption, break mean effective pressure, Sauter mean diameter, and emissions, including CO_2, NO_x, particulate matter, and smoke.

Table 1. Engine specification [21]

Type	Supercharged direct-injection 4-stroke
Bore x stroke [mm]	85 x 96.9
Displacement [cm^3]	550
Compression ratio	16.3
Fuel injection system	Common rail
Number of holes	7
Injection pressure [bar]	940, 1927
engine speed [rpm]	1500, 2000, 2200

Table 2. Fuel properties of fuels

Properties	Units	DF	35DFE	35BDE
Density (323 K)	kg/cm^3	830	818	835
Viscosity (323 K)	PaS	0.003	0.002226	0.002601
LHV	MJ/kg	42.5	44.519	43.933
Cetane number	-	48	38.7	35.2
Carbon content	%	0.87	0.87	0.8297
Oxygen content	%	0	0.004	0.123
Hydrogen content	%	0.126	0.126	0.0473

2. Analyzed Parameter

The Diesel-RK simulation provided the following key output parameters: A) Specific fuel consumption: Indicates the efficiency of fuel usage per unit of power output, B) Brake mean effective pressure: Represents the average effective pressure during the combustion cycle, C) Sauter mean diameter: Reflects droplet atomization quality and its influence on combustion and emissions, D). Exhaust emissions: Includes CO_2, NO_x, particulate matter, and opacity.

3. Assumption

The simulations assumed homogeneous combustion, no heat loss to the environment, and constant volumetric efficiency. Although the simulations provide a close approximation of real-world behavior, they have inherent limitations.

4. Materials

The materials utilized in this study consist of three primary fuels: conventional diesel fuel taken from Indonesian petroleum, biodiesel from blending 30% palm oil and 70% diesel fuel, and ethanol with 96% technical grade. These fuels were selected based on their relevance to current alternative energy research and their potential compatibility in compression ignition (CI) engines. To evaluate the combined effects of these fuels, a detailed and comprehensive simulation was performed using Diesel-RK software. The simulation incorporated various ethanol blending ratios—specifically 10%, 20%, 35%, and 50%—into both diesel and biodiesel base fuels. This systematic approach was designed to identify the most effective ethanol blending ratio with respect to both engine performance parameters and emission characteristics.

Such an evaluation is significant because many previous studies tend to focus solely on low-percentage ethanol blends or single fuel sources, often overlooking the broader range of ethanol content and its interaction with different base fuels. By examining a spectrum of blending ratios, this study aims to fill that research gap and provide deeper insight into the behavior of ethanol-diesel and ethanol-biodiesel mixtures under varying engine conditions.

For clarity, a consistent blend-naming convention is used throughout the analysis: for example, "35DFE" represents a fuel blend containing 35% ethanol with diesel fuel, while "35BDE" refers to a blend of 35% ethanol with biodiesel. "DF" denotes pure diesel fuel without any additives. The physical and chemical properties of each blend are summarized and compared in Table 2, while the technical specifications of the engine model used in the simulation are detailed in Table 1. The engine speeds considered in the simulation scenarios were set at 1500 rpm, 2000 rpm, and 2200 rpm, respectively, to represent typical operational ranges of CI engines in practical applications.

5. Specific Fuel Consumption

Specific fuel consumption (SFC) is measured by mass flow rate ($\dot{m}$) divided by power output (P), as expressed in Eq. (1). The specific fuel consumption is a measure of the fuel efficiency of the engine. The engine is more efficient if its specific fuel consumption is lower [22].

$$SFC\ (\frac{g}{kW}.h) = \frac{\dot{m}\ (\frac{g}{h})}{P\ (kW)} \quad \text{..} \quad (1)$$

6. Mean Effective Pressure (MEP)

The cylinder volume displaced per cycle divided by the work per cycle yields the engine performance pressure. The resulting parameter, known as mean effective pressure, has units per force per unit area [22], expressed in Eq. (2).

$$MEP\ (kPa) = \frac{P\ (kW).n\ .10^3}{V\ (dm^3.N\ (\frac{rev}{min})} \quad \text{..} \quad (2)$$

Where n is the number of crank revolutions, and V is cylinder volume.

7. Sauter Mean Diameter (SMD)

The Sauter Mean Diameter (SMD) is defined as the diameter of a sphere that has the same surface area-to-volume ratio as a given droplet or particle [23]. Understanding the SMD is essential in analyzing the combustion process, as it provides a measure of spray atomization quality and directly influences engine emissions and fuel ignition behavior [24]. Smaller fuel droplets evaporate more rapidly than larger ones during the spray combustion process. Since the volume of a large droplet is greater than that of a smaller one, it requires more time to evaporate completely [24]. Therefore, parameters such as droplet diameter, quantity, and surface area are important for determining the mean droplet size. The SMD can be calculated using Eq. (3).

$$SMD\ (32d) = \frac{\sum x_i^3\,\Delta ni}{\sum x_i^2 \Delta ni} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where *ni* is the number of droplets in a parcel and *xi* is the droplet diameter.

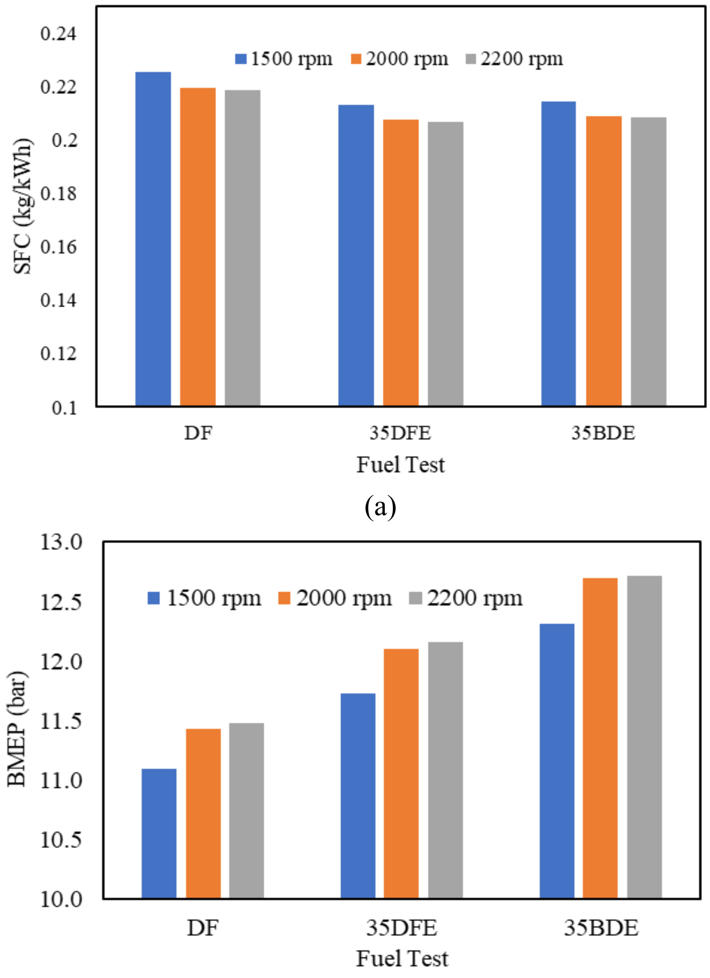
III. Results and Discussions

1. Engine Performances

Figure 1 illustrates the SFC and BMEP for the tested fuel blends. As shown in Figure 2(a), blending ethanol with diesel fuel, represented by 35DFE and 35BDE, resulted in a reduction in fuel consumption. This decrease is primarily attributed to the higher lower heating value (LHV) of the 35DFE blend [25]. Consequently, this improved combustion efficiency also contributes to an increase in BMEP [26], as seen in Figure 2(b).

Moreover, increasing engine speed was observed to reduce specific fuel consumption. This trend occurs because less fuel is required per unit of power output at higher speeds. The BMEP serves as an indicator of the combustion system's ability to efficiently convert fuel into mechanical output [12]. At 1500 rpm, the SFC for 35DFE was 5.42% lower than that of DF, while at 2200 rpm, 35BDE showed a 4.81% reduction in SFC compared to DF. These findings are consistent with those of previous studies on ethanol-diesel and ethanol-biodiesel blends [17,27].

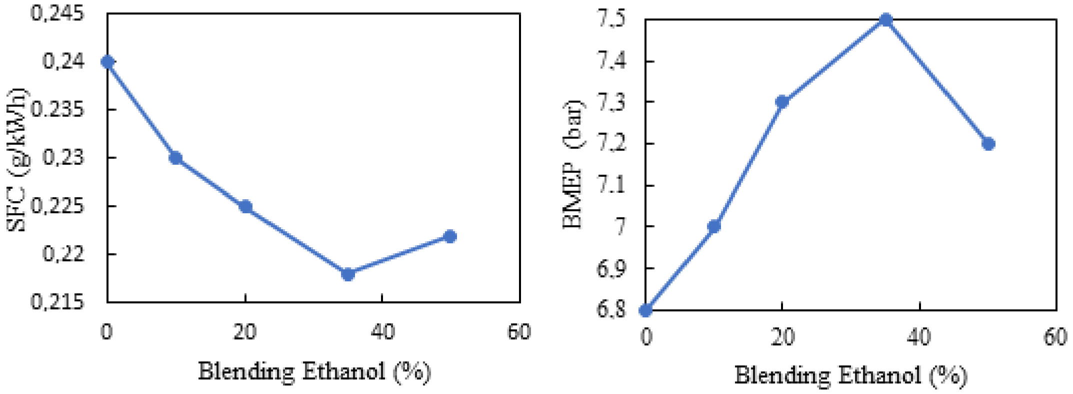
To further evaluate the impact of ethanol concentration, additional simulations were conducted using blending ratios of 10%, 20%, 35%, and 50% with both diesel (DFE) and biodiesel (BDE) base fuels. As presented in Figure 2, the SFC decreased with increasing ethanol content up to 35%, but slightly increased at 50%. Ethanol contains oxygen, which promotes more complete combustion of the fuel–air mixture that can lead to increased thermal efficiency and better oxidation of unburnt hydrocarbons [28]. Ethanol has around 34.7% oxygen by weight, which supports local oxygen-rich combustion zones within the cylinder; this can improve combustion homogeneity [29]. Although ethanol has a higher latent heat of vaporization, which initially cools the intake charge and can reduce peak combustion temperature, at 35% blending can prevent knocking and abnormal combustion [30]. Moreover, the decrease of SFC is likely due to the lower cetane number and higher volatility of ethanol at elevated concentrations [30]. The optimal SFC performance was observed at 20% and 35% ethanol blends. Similarly, BMEP increased with ethanol addition up to 35%, then declined at 50%. This pattern reflects the favorable effects of ethanol's oxygen content and higher LHV at moderate blending ratios, which enhance combustion efficiency. These simulation outcomes align with the experimental observations reported by Wang *et al.* [13] and Emmanuelle *et al.* [14].



(a)

(b)

Fig. 1. Engine performances. (a) Specific fuel consumption from fuels; (b) Brake mean effective pressures from fuels.



(a) (b)

Fig. 2. Engine performances with different blends of ethanol. (a) Specific fuel consumption from fuels; (b) Brake mean effective pressures from fuels.

2. Sauter Mean Diameter (SMD)

The integration of micro-scale parameters such as the Sauter Mean Diameter (SMD) provides valuable insights into fuel atomization characteristics and their influence on emissions—an aspect not commonly addressed in simulation-based studies. Figure 3 presents the SMD values for all fuel blends tested. The SMD represents the average droplet size, defined as the diameter of a sphere that has the same surface area-to-volume ratio as the fuel droplet population. It plays a crucial role in determining the effective surface area available for combustion, thereby influencing evaporation and combustion behavior [31].

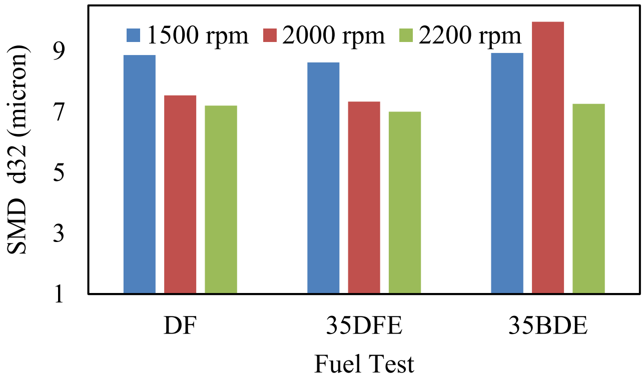


Fig. 3. Sauter mean diameter (SMD) from fuels.

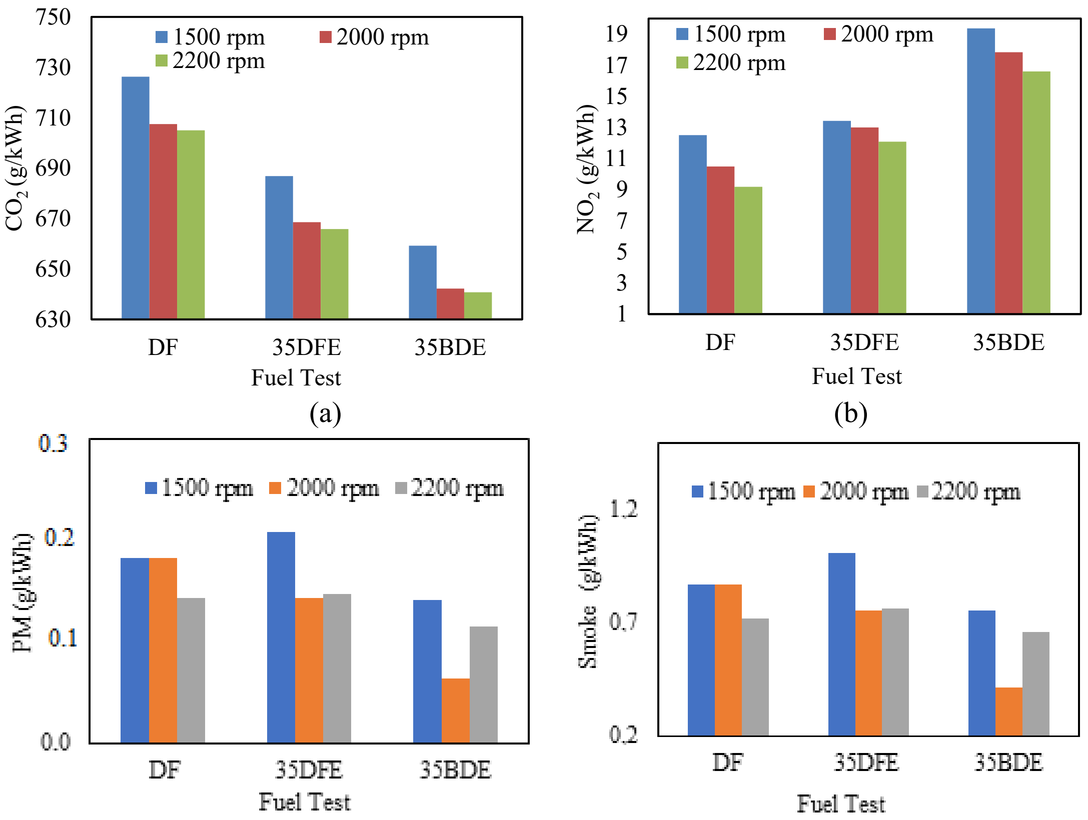
As shown in Figure 3, the SMD generally decreased with increasing engine speed for all blends, indicating improved atomization at higher speeds. However, at higher ethanol blending ratios, the SMD values for biodiesel–ethanol blends (BDE) increased slightly [31,32]. This trend is attributed to the higher viscosity and surface tension of biodiesel, which adversely affect atomization. The SMD for the 35BDE blend was higher than that of both 35DFE and DF, due to the inherently higher viscosity and density of biodiesel. Ethanol has lower viscosity, lower surface tension, and lower density. This property helps the fuel break up into smaller droplets more easily during injection, thereby reducing SMD [18,31]. Nevertheless, increasing the engine speed continued to reduce SMD across all fuel types, reinforcing the influence of injection dynamics on droplet breakup and atomization.

3. Emissions

Figure 4 presents the emission characteristics of all tested fuel blends. As shown in Figure 4(a), CO_2 emissions decreased with increasing engine speed. Ethanol blending was found to reduce CO_2 emissions, with the 35BDE blend achieving reductions of up to 9.23% and 9.11% at 2000 and 2200 rpm, respectively. This reduction is because ethanol has a lower carbon-to-hydrogen ratio and contains 34.7% oxygen by weight. When blended with diesel at a 35% concentration, the total carbon input per cycle is reduced, thereby reducing CO_2 formation during combustion [33]. Moreover, at higher engine speed, the engine burns fuel faster, and the effects of the lower carbon content in ethanol become more pronounced [34],[35].

Figure 4(b) shows that NO_2 emissions generally increased with engine speed. This increase is associated with the lower cetane number of ethanol-containing fuels, which leads to delayed ignition and the accumulation of fuel-air mixtures, thereby increasing peak temperatures and NO_2 formation [36]. At high speeds or loads, this ignition delay enhances the premixed combustion phase, resulting in higher peak temperatures and increased NO_x emissions. One study showed that the addition of ethanol (5–15%) increased NO_x by 16–22% due to this effect [37]. However, the 35BDE blend was able to reduce NO_2 emissions by up to 14.31% at 2200 rpm, likely due to the higher oxygen content in both ethanol and biodiesel, which supports more complete combustion and reduces NO_x formation.

Additionally, Figure 4(c) indicates that particulate matter (PM) emissions decreased with increasing engine speed across all fuel blends. A similar trend was observed for smoke opacity in Figure 4(d). Both PM and smoke were significantly reduced for the 35DFE and 35BDE blends, primarily due to the oxygenated nature of ethanol, which enhances combustion efficiency and limits soot formation. These results are consistent with previous studies on ethanol-blended diesel and biodiesel fuels [17],[27].



(a) (b)

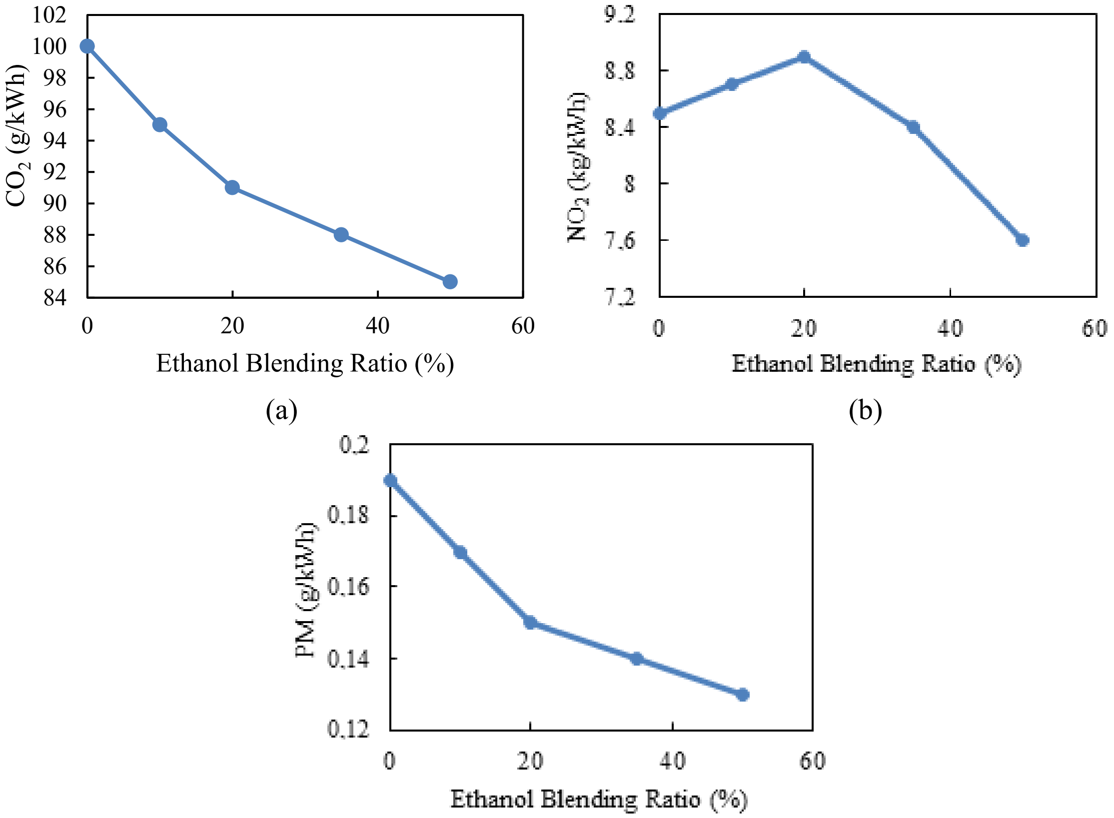
(c) (d)

Fig. 4. Emissions: (a) CO_2; (b) NO_2; (c) PM, and (d) Smoke

Figure 5 presents the emissions characteristics for different ethanol blending ratios. As shown in Figure 5(a), a 20% ethanol blend offered the best balance between CO_2 reduction. Figure 5(b) illustrates that NO_2 emissions followed a complex trend: they increased with engine speed for the 10% and 20% ethanol blends but decreased at 35% and 50%. This pattern is likely due to ethanol's lower cetane number, which delays ignition and reduces peak combustion temperatures.

Particulate matter (PM), as shown in Figure 5(c), was significantly reduced at ethanol blending levels of 20–35%. Notably, the BDE blends achieved up to 11% lower PM emissions compared to DF at 2200 rpm. Overall, the simulation results indicate that ethanol blending in the range of 20–35% offers the most effective compromise between enhancing engine performance and reducing emissions.

While the Diesel-RK simulation used in this study provides valuable insights into the effects of ethanol blending on CI engine performance and emissions, it is important to acknowledge its limitations. The simulation assumes homogeneous combustion, no heat loss to the environment, and constant volumetric efficiency. These assumptions may not fully capture real-world complexities such as in-cylinder turbulence, heat transfer losses, and varying air–fuel mixing dynamics.



(a) (b)

(c)

Fig. 5. Emissions by different blending ethanol: (a) CO_2; (b) NO_2; and (c) PM,

Moreover, the spray breakup, ignition delay, and combustion behavior are approximated using theoretical and empirical models that may not represent actual fuel behavior under transient or high-load conditions. As a result, the predicted emission values and performance trends—although consistent with literature—require further validation through experimental testing.

To enhance the reliability and applicability of these findings, future work will involve controlled engine bench tests using the same ethanol blending ratios (10%, 20%, 35%, and 50%) on both diesel and biodiesel base fuels. These experiments will be conducted under varying engine speeds and loads to validate simulation outcomes and capture parameters such as real-time cylinder pressure, ignition delay, brake thermal efficiency, and exhaust gas temperature. In addition, exhaust gas analyzers will be used to measure actual emissions of CO_2, NO_x, PM, and smoke. This empirical approach will provide a robust framework for confirming the simulation results and guiding practical engine modifications for ethanol fuel application.

IV. Conclusions

This study demonstrated that blending ethanol with diesel and biodiesel fuels significantly influences the CI engine and emissions. A 35% ethanol blend was found to offer an optimal balance, leading to reductions in specific fuel consumption and improvements in brake mean effective pressure, particularly at higher engine speeds. Emission analysis revealed that CO_2 emissions decreased by up to 9.23% and 9.11% at 2000 and 2200 rpm, respectively, when using biodiesel–ethanol blends. This is because ethanol contains oxygen, which increases the combustion of the fuel-air mixture more completely, so that it can increase thermal efficiency and better oxidation. Furthermore, particulate matter and smoke were substantially reduced due to the oxygenated nature of ethanol, which enhances combustion completeness. Although SMD was slightly higher for biodiesel-based blends due to greater viscosity and density, the overall atomization quality remained within acceptable limits. The study concludes that ethanol blending ratios between 20% and 35% provide the best trade-off between engine performance and emission reduction. A 35% ethanol blend can have a substantial impact on engine design, fuel policy, and sustainable transportation plans in Indonesia. Higher ethanol mixes may necessitate changes to engine components to ensure compatibility and performance. At the policy level, the implementation of 35% ethanol blend will involve changes to fuel standards, infrastructure preparation, and regulatory frameworks. Strategically, adopting 35% ethanol blend promotes national renewable energy and carbon emission reduction targets, but it must be combined with bigger strategies for automotive technology transitions and agricultural sustainability.

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