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Usage of third generation propanol/diesel blends with carbon nanotubes as sustainable diesel alternative

Karbon nanotüplerle zenginleştirilmiş üçüncü nesil propanol/dizel karışımlarının sürdürülebilir dizel alternatifi olarak kullanımı

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Abstract

This investigation examines the influences of multi-walled carbon nanotubes (MWCNT) as an additive in propanol-diesel blends on the combustion, performance, and exhaust emission behavior of a compression ignition engine. Test fuels comprised propanol-diesel blends with MWCNT addition of 50, 100, and 150 ppm, evaluated against ultra-low sulfur diesel as the reference fuel. Experimental results revealed that MWCNT-enhanced blends showed significant enhancements in engine efficiency, with brake thermal efficiency exhibiting improvements of up to 16% and brake specific fuel consumption showing reductions of up to 5.6% relative to baseline diesel. Combustion analysis indicated reduced maximum in-cylinder pressures and elevated peak heat release rates for MWCNT-containing blends. Exhaust gas analysis revealed carbon dioxide and nitrogen oxide emissions exhibited reductions up to 18% and 42%, respectively, compared to diesel fuel. However, carbon monoxide emissions were slightly lower and an increase in unburned hydrocarbon was observed. These experimental findings indicate that MWCNT-enhanced propanol-diesel blends represent a viable approach for improving compression ignition engine thermal efficiency though further optimization is required to mitigate CO and HC formation.

Keywords: Biofuel; MWCNT; Propanol; Diesel engine

Öz

Bu araştırma, çok duvarlı karbon nanotüplerin (MWCNT) propanol-dizel karışımlarında yakıt katkı maddesi olarak kullanımının, sıkıştırma ateşlemeli bir motorun yanma, performans ve egzoz emisyon davranışı üzerindeki etkisini incelemektedir. Test yakıtları, referans yakıt olarak ultra düşük kükürtlü dizel ile karşılaştırılan, kütlece 50, 100 ve 150 ppm MWCNT içeren propanol-dizel karışımlarından oluşmuştur. Deneysel sonuçlar, MWCNT katkılı yakıt karışımlarının motor verimliliğinde önemli iyileşmeler sağladığını göstermektedir; fren termal verimliliğinde %16'ya kadar artış, özgül yakıt tüketiminde ise %5.6'ya kadar azalma gerçekleştiği tespit edilmiştir. Yanma analizleri, MWCNT içeren karışımlar için maksimum silindir içi basınçlarda düşüş ve en yüksek ısı salınım oranında artış olduğunu göstermiştir. Egzoz gazı analizleri, karbondioksit ve azot oksit emisyonlarında sırasıyla %18 ve %42'e kadar azalma olduğunu göstermiştir. Buna karşılık, karbonmonoksit emisyonları az miktarı azalmıştır ve yanmamış hidrokarbon ise artış göstermiştir. Bu deneysel bulgular, MWCNT ile zenginleştirilmiş propanol-dizel karışımlarının, sıkıştırma ateşlemeli motorlarda termal verimliliği rağmen artan karbon monoksit ve hidrokarbon oluşumu azalmak için daha ileri iyileştirmeye ihtiyaç vardır.

Anahtar kelimeler: Biyoyakıt; MWCNT; Propanol; Dizel motor

1 Introduction

Compression ignition engines are powered by fossil-fuels continue to be a dominant power source in transportation, agriculture, and industry due to their high efficiency, robustness, and long operational lifespan [1]. However, the extensive reliance on fossil fuels leads to serious environmental and energy security concerns, primarily due to greenhouse gas emissions, especially carbon dioxide (CO_2), which plays a central role in driving climate change [2]. The environmental impacts of these include rising global temperatures, accelerated polar ice mass loss, increased frequency and severity of extreme weather events, and widespread disruption of ecological processes and biodiversity patterns [3]. These alarming issues underscore the urgent need to transition toward renewable and sustainable energy technologies to mitigate environmental degradation and protect human health [4-6]. Integrating biofuels in this way not only advances environmental objectives but also strengthens energy security by reducing reliance on finite petroleum resources [7]. Besides, the biofuel resources are abundant [8].

Among biofuels, bioalcohols have attracted growing attention. Alcohols such as methanol, ethanol, propanol, butanol, and pentanol can be utilized in compression-ignition engines with no system alterations [9-10]. The application of bioalcohols offers advantages including cleaner combustion, lower exhaust emissions, and the potential use of waste biomass for fuel production. Unlike petroleum fuels, alcohols can be synthesized from renewable biomass sources such as agricultural residues, municipal waste, and lignocellulosic biomass, supporting a more sustainable

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energy cycle [11]. Among higher alcohols, propanol stands out due to its favorable physicochemical properties. Compared to lower alcohols, propanol exhibits lower polarity, which enhances its miscibility with diesel and allow for stable blends with higher concentration of biofuel [12-13]. Despite the lower heating value of propanol, its high oxygen content promotes enhanced complete combustion, resulting in reduced emissions of pollutants [14].

To further improve the performance of biofuel blends, numerous studies have explored the use of additives such as metallic nanoparticles, antioxidants, and carbon-based nanomaterials. Among these additives, multi-walled carbon nanotube (MWCNT) has identified as effective for compression ignition engine applications owing to their superior physicochemical properties. Their exceptional thermal conductivity, large surface area, and catalytic capabilities contribute to improved fuel atomization, enhanced combustion, and reduced exhaust emissions [15]. Solmaz et al. [16] investigated the effects of incorporating 100 ppm MWCNT to a biodiesel-diesel blend under various engine loads. Their findings revealed that the addition of MWCNT was shortened combustion duration relative to neat diesel, resulting in a peak indicated thermal efficiency of 33.16%. The enhancement was mainly associated with reduced heat losses and enhanced in-cylinder combustion reactions within the cylinder, which also led to reductions of 41% in hydrocarbon (HC), 36% in carbon monoxide (CO), and 31% in soot emissions. However, the higher in-cylinder temperatures associated with improved combustion resulted in increased nitrogen oxides (NO_x) emissions. In the study by Indira et al. [17], slaughterhouse waste biodiesel was blended at 20% with diesel, and 50 ppm of MWCNT was incorporated into the mixture. Their results showed that the MWCNT-added blend led to notable reductions in smoke, CO, and CO_2 emissions, while NO_x and HC emissions increased. The heat release rate (HRR) was higher for the nanoparticle-enhanced fuel, and the cylinder pressure (CP) exhibited a slight increase. Regarding performance, both brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) improved when MWCNT was introduced. M. Nachippan et al. [18] studied 20% hemp biodiesel-80% diesel blends enhanced with 25, 50, and 75 ppm of MWCNT. Their findings indicated that the incorporating of MWCNT into the blends was reduced hazardous emissions including HC, CO, NO_x, and smoke. On the other hand, the effects on fuel consumption and BTE were dependent on the fuel blend and operating conditions. Harsha et al. [19] examined the effects of adding 20 ppm and 40 ppm of MWCNT to a fuel blend containing 20% biodiesel and 80% diesel. An increase in BTE was observed for the blend with 20 ppm MWCNT. In addition, fuel consumption and emissions such as nitrogen monoxide, CO, and smoke were reduced for the MWCNT-containing blends. Likewise, Singh et al. [20] investigated hybrid biodiesel blends (10%, 20%, and 30% biodiesel) containing 30 ppm MWCNT. The inclusion of MWCNT reduced HC, CO, NO_x, and smoke emissions while deteriorating CO_2 emissions compared to both the hybrid biodiesel blends and neat diesel, highlighting the complex trade-offs in emission profiles.

Although previous studies examined either propanol-diesel blends or MWCNT-enhanced biodiesel fuels separately, no study systematically investigated the combined influence of propanol and MWCNTs in diesel engines. Therefore, this investigation represents the first systematic assessment of MWCNT-enhanced propanol-diesel blends, addressing an existing gap in the literature regarding the synergistic roles of oxygenated biofuels and nanomaterial additives. The addition of MWCNTs to propanol-diesel blends could harness the catalytic and thermal advantages of the nanotubes to enhance combustion efficiency, reduce harmful emissions, and improve overall engine performance. Accordingly, this study uniquely examines the effects of MWCNT addition at concentrations of 50, 100, and 150 ppm in propanol-diesel blends using a mono-cylinder diesel engine. By evaluating their combined effects, this study aims to demonstrate the potential of these blends as cleaner fuel alternatives capable of contributing to environmental compliance and supporting the shift toward sustainable energy use.

2 Materials and methodology

2.1 Fuel preparation and characterization

Ultra-low sulfur diesel (D0) was used as the reference fuel for this experimental investigation, and all subsequent fuel blends compared to D0. The test fuels consisted of diesel and propanol blended at a 75:25 volume ratio with the addition of MWCNT at concentrations of 50, 100, and 150 ppm per liter to improve diesel engine performance. These blends were named P25CNT50, P25CNT100, and P25CNT150, respectively. During the blending process, an ultrasonic mixer operating at a frequency of 24 kHz and a power of 60 kW was employed for 30 minutes to ensure uniform dispersion of the nanotubes throughout the fuel blends. The blending temperature was maintained at 25 ±2°C. The MWCNT-containing blends were visually monitored for sedimentation, and all samples exhibited good stability. The main features of the test fuels are presented in Table 1.

All fuel preparation procedures were carried out in accordance with standard laboratory safety practices. All propanol and MWCNT handling were performed in a fume hood, and full protective equipment, including gloves, eye protection, and a respirator for nanotube work, was used throughout blending.

Table 1. Main features of the test fuels

Characteristic	ULSD	Propanol [9]	P25CNT50	P25CNT100	P25CNT150
Heating value (kJ/kg)	45977	30600	42133	42160	42198
Density (kg/L) at 15 °C	0.797	0.803	0.773	0.773	0.774
Viscosity (mm^2/s) at 40 °C	2.91	1.959	2.12	2.11	2.04

2.2 Nanomaterial analysis

Figure 1 displays scanning electron microscope (SEM) energy-dispersive X-ray (EDX) analyses of the tested MWCNT sample. The nanotubes display an entangled and porous surface morphology. Carbon is the dominant element (≈90 wt%), confirming the carbonaceous structure of the material. Trace amounts of aluminum (Al) and silver (Ag) detected in the EDX spectrum originate from the SEM sample mounting stub and conductive adhesive tape rather than the nanotube material itself. Therefore, these elements are considered external contamination introduced during sample preparation.

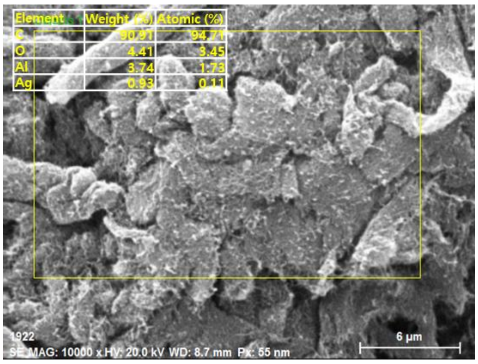

Figure 1. SEM EDX visuals for the tested MWCNT particles.

Figure 2 presents the Transmission Electron Microscopy (TEM) images of the analyzed MWCNT particles. These MWCNTs exhibit outside diameters ranging from 8-10 nm and inside diameters spanning 5-15 nm. The MWCNT sample used in this work was non-functionalized. Figure 2 TEM visuals of MWCNT powder.

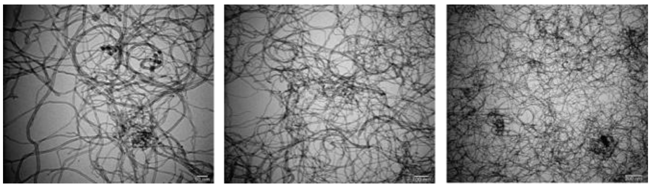

Figure 2. TEM visuals of MWCNT powder.

Table 2 provides the detailed specifications of MWCNT used in this study.

Table 2. Characteristics of MWCNT used in this study.

Property	Unit	MWCNT
Production method	–	CVD
Color	–	Black
Outside diameter	nm	8–10
Inside diameter	nm	5–15
Length	µm	1–3
Compressed density	g/cm³	0.25
COOH content	%	–
Ash content	Wt.%	1.5
Actual density	g/cm³	2.4
Electrical conductivity	S/cm	98
Thermal conductivity [21]	W/mK	3000
Specific surface area	m²/g	290

Figure 3 presents the thermogravimetric analysis (TGA) and derivative thermogravimetric (DTG) curves of the MWCNT sample, performed under nitrogen atmosphere at a heating rate of 10 °C·min⁻¹. The nanotubes exhibited high thermal stability up to approximately 390–410 °C, marking the onset of decomposition. A rapid weight-loss event was observed at a DTG peak temperature of around 495–510 °C, associated with structural oxidation and breakdown of the graphene layers. The decomposition process continued until ~600 °C, where the sample stabilized, with a total mass loss of approximately 88–92%, leaving a 8–12% residual content attributed to metallic catalyst remnants and carbonaceous ash.

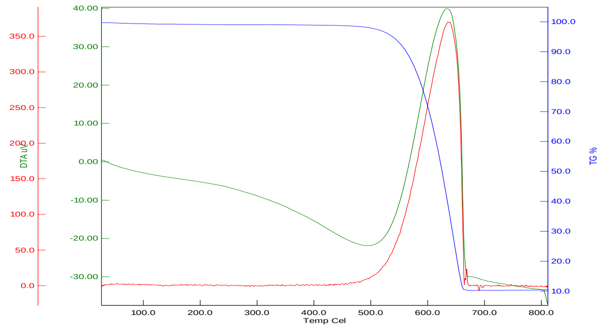

Figure 3. TGA for MWCNT.

2.3 Fuel preparation and characterization

The tests were employed on a Kirloskar TV1 engine test stand, equipped with a data logger, exhaust gas analyzer, piezoelectric pressure sensor, crank encoder, data logger, electronic precision scale and additional instrumentations to evaluate engine combustion, performance and emissions. The engine features a four-stroke, a mono-cylinder with a variable compression ratio, water-cooling system, and direct fuel injection. The experimental analysis was maintained at a constant 1500 rpm under four different loads corresponding to idle, 1.5 bar, 3.1 bar and 4.6 bar Brake Mean Effective Pressure (BMEP), supported by a dynamometer. The main specifications measurement ranges of the test equipment are provided in Table 3.

Table 3. Main specifications measurement ranges of the test equipment.

Parameter	Specification
Engine brand and type	Kirloskar TV1
Stroke	Four-stroke
Total displacement	0.661 liter
Connecting rod length	234 mm
Start of injection	0-25° bTDC
Bore / Stroke	87 / 110 mm
Dynamometer cooling type	Water-cooled
Dynamometer load indicator	Digital, 0-50 kg
Dynamometer type	Eddy current
Compression ratio	17.5:1
Maximum power	5.2 kW@1500 rpm
Crank angle resolution	Resolution 1°
Crank angle maximum speed	5500 rpm
Pressure sensor	0-200 bar ±0.5

Table 3. (cont.) Main specifications measurement ranges of the test equipment.

Parameter		Specification
Exhaust Analyzer	HC	0-20000 ppm ±1
	CO_2	0-21.0% ±0.1
	NO_x	0-10000 ppm ±1
	CO	0-10.0% ±0.001
	O_2	0-21.7% ±0.01

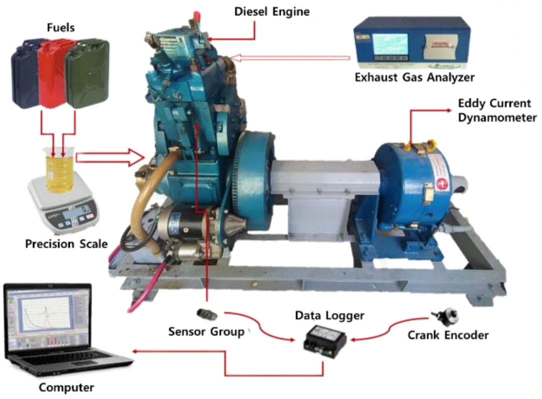

Figure 4. A schematic demonstration of the experimental setup

A crank angle encoder was mounted on the crankshaft to monitor engine RPM and crank angle in real time. A piezo-electric pressure sensor was fitted to the engine cylinder to measure internal pressure. The cylinder pressure data was recorded at a crank angle resolution of 1° CA, with an acquisition rate of 10 cycles per operating point. Each data point shown in the combustion analysis represents the averaged value of these 10 engine cycles to reduce cycle-by-cycle variation. ICEngineSoft V9.0 software was used for engine control and real-time data logging at each crank angle. These devices calculate combustion parameters such as CP, mean gas temperature (MGT), rate of pressure rise (RoPR), and HRR. A schematic demonstration of the experimental setup is shown in Figure 4.

Exhaust emissions were measured with a Capalec CAP 3200 gas analyzer, with its sensor placed 1.5 meters from the exhaust manifold. For fuel injection, a nozzle was operated at a constant fuel injection pressure of 200 bars. Fuel consumption was measured gravimetrically using a graduated fuel burette, allowing real-time determination of fuel mass flow rate. The air–fuel ratio was monitored using the data acquisition system and exhaust gas analyzer readings and was maintained within normal diesel combustion limits under each load condition. During all experiments, the coolant temperature was regulated at 75 ± 2 °C using the engine's water-cooling system, and the lubricating oil temperature was maintained at 70 ± 3 °C to ensure consistent thermal conditions. The engine was allowed to warm up before each test, and steady-state conditions were confirmed prior to data recording. Each test was repeated three times, and average values were used to plot combustion, performance, and emission results.

2.4 Error analysis

Device performance is assessed through calibration procedures and operational testing across designated parameter ranges. The investigated variables each demonstrate a relationship with error frequency in the tested equipment. Total measurement uncertainty is derived by combining instrumental uncertainties with experimental errors. This study employs the root mean square method as a key analytical approach to quantify the cumulative uncertainty in engine performance measurements. Equation (1) defines the total experimental error for each engine operation, with the specific uncertainty values obtained from this investigation detailed in Table 4.

$$\Delta U = \sqrt{\left(\frac{\partial U}{\partial x_1}\Delta x_1\right)^2 + \left(\frac{\partial U}{\partial x_2}\Delta x_2\right)^2 + \cdots + \left(\frac{\partial U}{\partial x_n}\Delta x_n\right)^2} \tag{1}$$

Table 4. Accuracy and uncertainty values for measuring parameters.

Parameters	Variables	Instruments	Uncertainty (%)	Total uncertainty (%)
Brake power	Speed	Speed measuring unit	±0.3	±1.46
		Encoder	±0.6	
	Load	Load indicator	±1.3	
BSFC	Fuel consumption	Fuel measuring unit	±2.5	±2.89
	Brake power	Calculated above	±1.46	
BTE	BSFC	Calculated above	±2.89	±3.23
	Brake power	Calculated above	±1.46	
Exhaust analyzer	HC	-	±0.5	±0.5
	CO	-	±0.3	±0.3
	NO_x	-	±0.29	±0.29
	CO_2	-	±0.95	±0.95

This equation computes the combined uncertainties associated with measured parameters including total fuel consumption, brake power, BSFC, BTE, and emission components (NO_x, CO_2, CO, and HC) for defined operating conditions. When these individual uncertainties are propagated through the root mean square calculation, the resultant overall experimental uncertainty is determined to be ±3.42%.

3 Result and discussion

3.1 Combustion parameters

Figure 5 illustrates the variation of HRR and CP versus crank angle with engine load for D0 and MWCNT-propanol-diesel blends. Based on CP data shown in the provided figure, the MWCNT-enhanced propanol-diesel blends demonstrated consistently lower peak CPs with an average of 6.2% for P25CNT50, 12.4% for P25CNT100 and 14.7% for P25CNT150 compared to D0. This trend order indicates that as MWCNT concentration increased from 50 to 150 ppm, peak CPs progressively decreased. The trend became more pronounced at higher loads, where D0 reaches ~62 bar at 4.6 bar BMEP while P25CNT150 achieved only ~55 bar, representing a significant 11% reduction in CP. The primary reason for this behavior was the substantially lower heating value of propanol compared to D0, which resulted in less energy density and directly translates to reduced energy release per unit mass of fuel burned. The combustion start was postponed, and the ignition duration was shortened for the MWCNT-enhanced blends compared to D0. This can be attributable to the fact that the lower cetane number of propanol slightly delayed the ignition start, shifting peak CP timing. This delayed ignition with shortened combustion duration can be attributed to the ignition characteristics of propanol. However, the catalytic effects of MWCNTs, which may initially delay ignition due to altered fuel properties but then accelerated the combustion process once initiated through enhanced reaction kinetics and improved heat transfer.

Based on the HRR data presented in the provided figure, the MWCNT-enhanced propanol-diesel blends demonstrated higher peak HRRs, with an average increase of 21.2.5% for P25CNT50, 11.2% for P25CNT100 and 8.3% for P25CNT150 compared to D0. The HRR of the MWCNT-propanol blends showed a substantial increase at idle load, where the peak HRR was higher than that of D0. This increase reflects more concentrated combustion due to improved flame development and heat transfer supported by MWCNTs. For P25CNT blend, the superior thermal conductivity of MWCNT acted as a combustion enhancer, promoting finer fuel droplet dispersion and faster flame propagation. This enhanced HRR pattern can be attributed to the catalytic effect of MWCNTs, which promoted better fuel-air mixing and accelerated the combustion kinetics through their high thermal conductivity and large surface area. The sharper and more pronounced HRR peaks in the MWCNT blends indicate more efficient combustion with reduced combustion duration, suggesting improved fuel utilization compared to D0. P25CNT50 likely exhibited the highest HRR peak, followed by P25CNT100 and P25CNT150, as higher MWCNT concentrations accelerated ignition and energy release. This could be due to agglomeration at higher concentrations, reducing effective dispersion, a phenomenon supported by literature [22]. Propanol's oxygen content further intensified HRR by supporting more complete combustion thanks to its higher latent heat of evaporation which contrarily caused a slight delay in HRR onset.

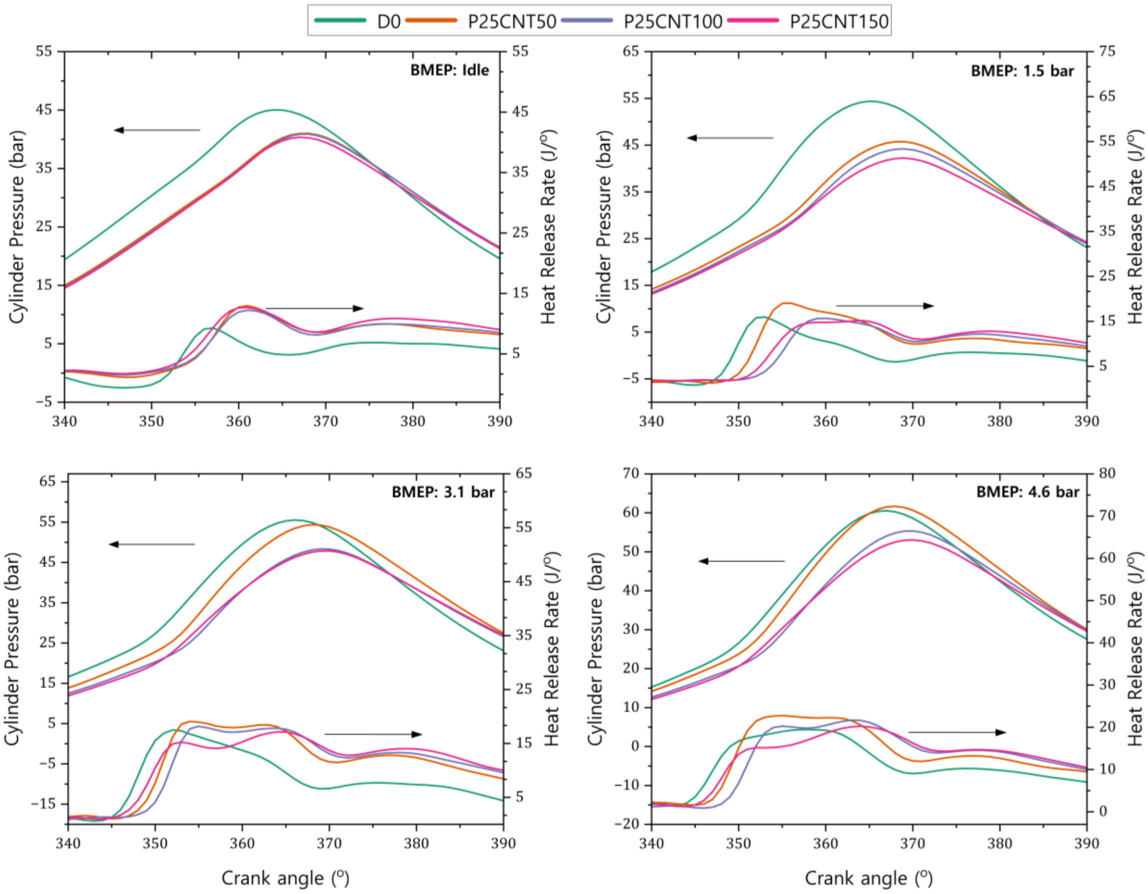

Figure 5. Variation of HRR and CP versus crank angle with engine load for D0 and MWCNT-propanol-diesel blends.

Figure 6 presents the variation of RoPR and MGT versus crank angle with engine load for D0 and MWCNT-propanol-diesel blends**.** Based on MGT data, the MWCNT-enhanced propanol-diesel blends demonstrated elevated MGT with an average of 4.4%, 2.0% and 1.5% for P25CNT50, P25CNT100 and P25CNT150 on average compared to D0. As the load increased, the intensified combustion from higher fuel injection resulted in increased MGTs. The MGT curves revealed that the MWCNT-enriched blends consistently achieved higher peak MGTs during the combustion process, which correlates with the enhanced HRR observed in these fuels. This can be attributed to the superior thermal conductivity of MWCNTs and their catalytic properties, which promote more complete and intensive combustion reactions. The higher MGT values in the MWCNT blends indicated improved combustion efficiency and better energy conversion from the fuel, as the elevated temperatures facilitated more thorough oxidation of fuel molecules. D0 exhibited lower peak MGT, reflecting its slower combustion process by limiting its performance due to the absence of oxygen-rich additives. This behavior supports the previous observations of shortened combustion duration and enhanced HRR in the MWCNT blends, where the combination of delayed ignition and accelerated combustion kinetics results in more concentrated energy release that results in higher MGTs.

Based on RoPR data shown in the figure, the MWCNT-enhanced propanol-diesel blends exhibited lower RoPR values with reductions of 4.9% for P25CNT50, 8.8% for P25CNT100 and 21.6% for P25CNT150 on average compared to D0. MWCNT acted as combustion catalysts, providing additional surface area and active sites that promoted more complete and controlled fuel oxidation, leading to a smoother pressure rise rather than sharp combustion peaks. The enhanced fuel atomization achieved through MWCNT addition created smaller, more uniform fuel droplets that burn more gradually and evenly throughout the combustion chamber, reducing the intensity of pressure rise. Moreover, propanol's lower cetane number and auto-ignition resistance allowed for better fuel-air mixing before the start of combustion. The improved thermal conductivity of MWCNT-enhanced fuels facilitated better heat dissipation within the fuel mixture, preventing localized hot spots that could cause rapid pressure spikes. Ignition delay plays an important role in shaping both RoPR and MGT. A longer ignition delay allows a greater amount of fuel-air mixture to accumulate before auto-ignition occurs. When combustion finally started, this accumulated mixture burns rapidly in the premixed phase, which typically increased the RoPR. However, in the MWCNT-enhanced blends, the low cetane number of propanol increased ignition delay, but the thermal conductivity and catalytic surface activity of MWCNTs promoted faster heat transfer and more uniform flame propagation once ignition initiated.

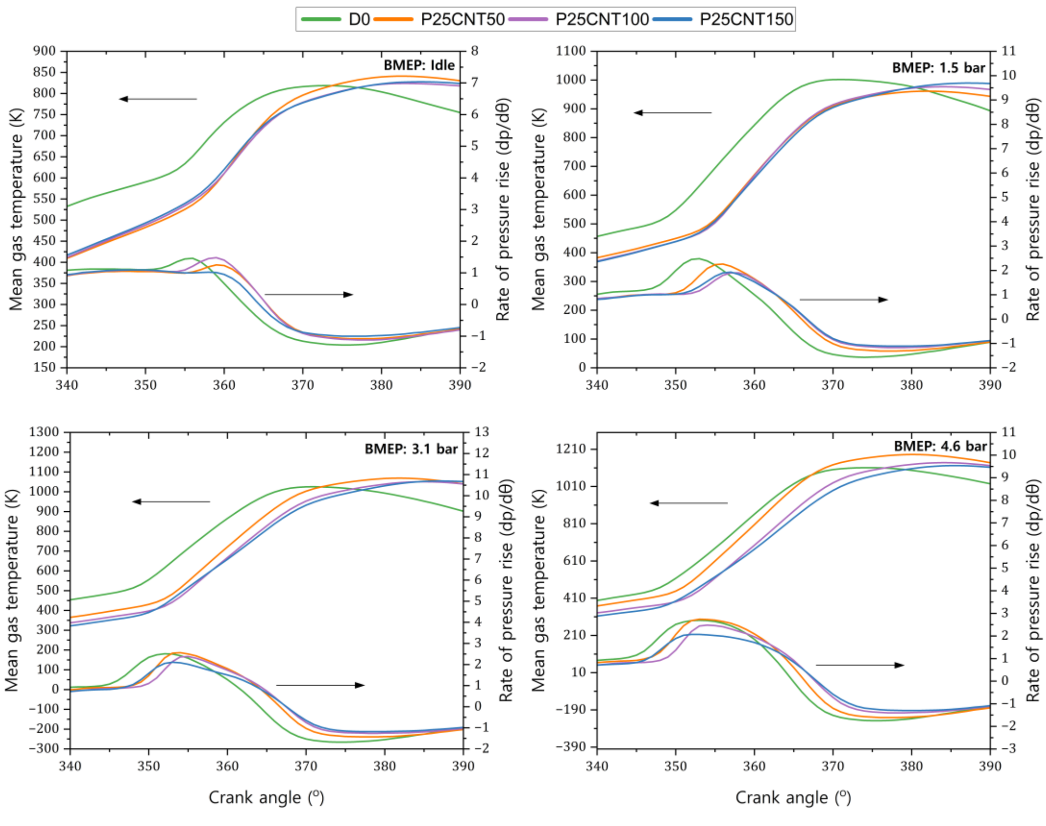

Figure 6. Variation of RoPR and MGT versus crank angle with engine load for D0 and MWCNT–propanol–diesel blends.

This resulted in a smoother combustion process with a moderated RoPR compared to D0. Meanwhile, MGT increased because the improved combustion efficiency accelerated oxidation reactions during the main heat release phase, concentrating heat release into a shorter crank-angle duration. Thus, propagation was faster while RoPR was less abrupt due to the more distributed thermal and chemical reaction zones facilitated by MWCNTs.

3.2 Performance parameters

Figure 7 illustrates the variation of BTE and BSFC with engine load for D0 and MWCNT-propanol-diesel blends. Based on the BTE data presented in the figure, the MWCNT-enriched blends consistently exhibited higher BTE values, with improvements of 8.8% for P25CNT50, 11.1% for P25CNT100 and 16% for P25CNT150 on average. This enhancement indicates a more effective conversion of fuel's chemical energy into useful mechanical work. This can be attributed to the multifaceted benefits of MWCNT additives, which enhanced combustion completeness through their catalytic properties, improved heat transfer rates due to their exceptional thermal conductivity, and promote better fuel-air mixing through enhanced atomization characteristics. This facilitates the formation of reactive oxygen molecules and accelerates the oxidation of fuel molecules. Additionally, the enhanced local radical formation around the nanotube surfaces contributed to improved ignition quality and faster flame propagation. These catalytic effects collectively led to a more efficient and complete combustion process during the premixed phase, resulting in higher BTE. The increase in BTE does not originate from the energy density of the fuel blend, since propanol has a lower heating value than diesel. Instead, the improvement is associated with changes in combustion phasing and heat-release characteristics. The HRR curves showed that the MWCNT-assisted blends exhibited more concentrated heat release during the main combustion phase, which increased the proportion of heat converted to mechanical work. The thermal conductivity of MWCNTs enhanced in-cylinder heat transfer and promoted more uniform flame propagation, while their catalytic surface accelerated oxidation reactions once ignition occurred. As a result, a greater portion of the available fuel energy was effectively utilized, which explained the observed increase in BTE despite the lower heating value of propanol. When interpreted alongside the HRR curves, the BTE results are consistent with the observation that MWCNTs promote faster flame development and reduce combustion losses, enabling more effective utilization of the available fuel energy despite the lower heating value of propanol.

According to BSFC data presented in the figure, although P25CNT blends possess lower heating values compared to D0. At low engine loads, the BSFC values of the propanol-containing blends remain similar to or slightly higher than diesel due to the longer ignition delay and high latent heat of vaporization of propanol, which reduces the local mixture temperature during the early combustion phase and delays the development of stable flame propagation. As load increases, combustion temperature and reaction rates increase, and the thermal conductivity and catalytic surface activity of MWCNTs support more efficient oxidation and heat release. The reduced BSFC values suggest that the MWCNT additives enable more complete combustion with better fuel utilization, allowing the engine to produce the same power output while consuming less fuel. P25CNT150 showed the best performance with an average improvement of 5.6% in BSFC while P25CNT100 performed an average 1.4% decrease of BSFC. On the other hand, P25CNT50 showed a slight increase of 0.6% on average.

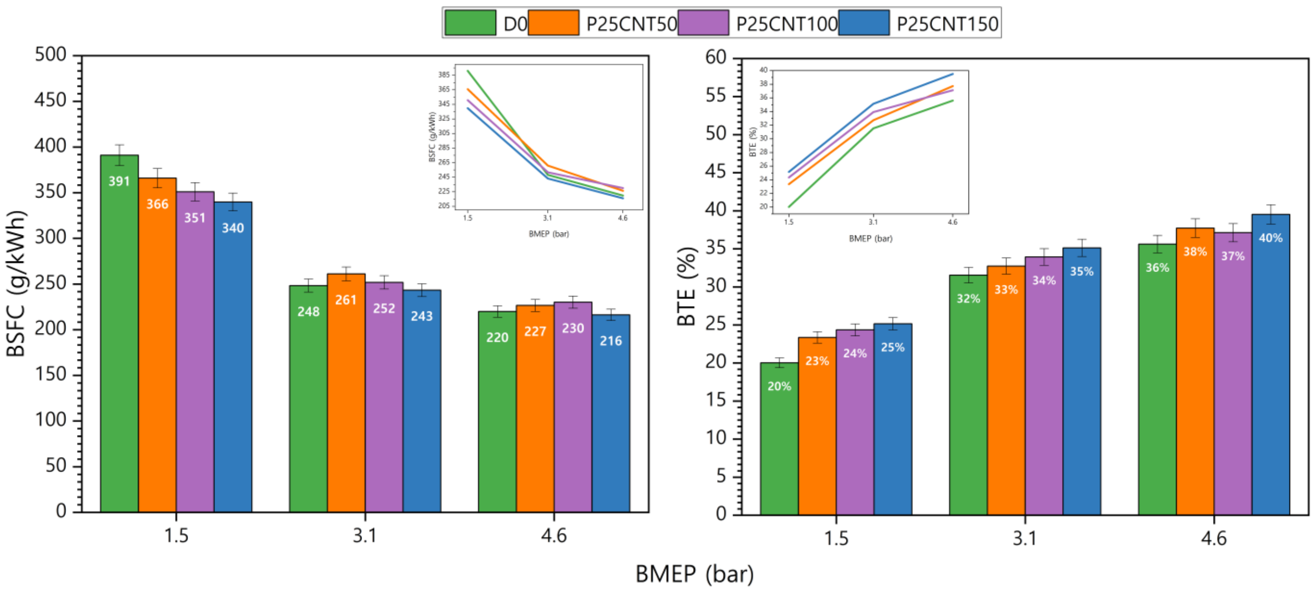

Figure 7. Variation of BTE and BSFC with engine load for D0 and MWCNT-propanol-diesel blends.

3.3 Emission parameters

Figure 8 displays the variation of CO, CO_2, HC and NO_x emissions with engine load for D0 and MWCNT-propanol-diesel blends. The CO emissions for test fuels (P25CNT50, P25CNT100, P25CNT150) were slightly lower or at the same level as those of D0. The CO results showed a load-dependent trend. At lower loads, the oxygen content of propanol promoted more complete oxidation, resulting in CO levels that were similar to or slightly lower than those of D0 (approximately 0.045–0.06 %vol). However, at higher loads, the reduced in-cylinder oxygen availability and locally fuel-rich regions caused CO to increase slightly, reaching values in the range of 0.065–0.085 %vol, which was consistent with the behavior of oxygenated fuels under diffusion-controlled combustion. The high oxygen content of propanol promoted more complete combustion, reducing incomplete combustion products including CO emissions. MWCNT addition was likely to enhance fuel atomization and combustion efficiency due to their high surface area and catalytic properties, further decreasing CO emissions. Additionally, MWCNT additives can reduce CO by improving oxidation. As MWCNT concentration increased, CO emissions expected to decrease progressively. CO_2 emissions from the figure for the test fuels were likely same level to or slightly lower than those for D0, with an average decrease of 13.3% for P25CNT50, 16.5% for P25CNT100, 18.7% for P25CNT150. The decrease in CO_2 emissions is primarily related to the lower carbon-to-hydrogen ratio of propanol compared to D0. On a mass basis, the carbon content of propanol is approximately 0.52 gC/g fuel, while diesel contains approximately 0.86 gC/g fuel, meaning that less carbon is introduced per unit of fuel. However, the lower heating value of the test fuels required more fuel to achieve the same amount of power output, likely limiting CO_2 reductions. MWCNT's catalytic effects enhanced combustion efficiency, further reducing incomplete combustion products and improving CO_2 emissions. As MWCNT concentration increased, CO_2 emissions decreased, with P25CNT150 showing the lowest CO_2 emissions. The improved BTE observed in the MWCNT blends means that less fuel was required to produce the same power output, which could offset the increased CO_2 formation per unit of fuel burned. Although the MWCNT additives improve combustion uniformity, the dominant factor influencing CO_2 formation in these blends is the reduced carbon content introduced by propanol.

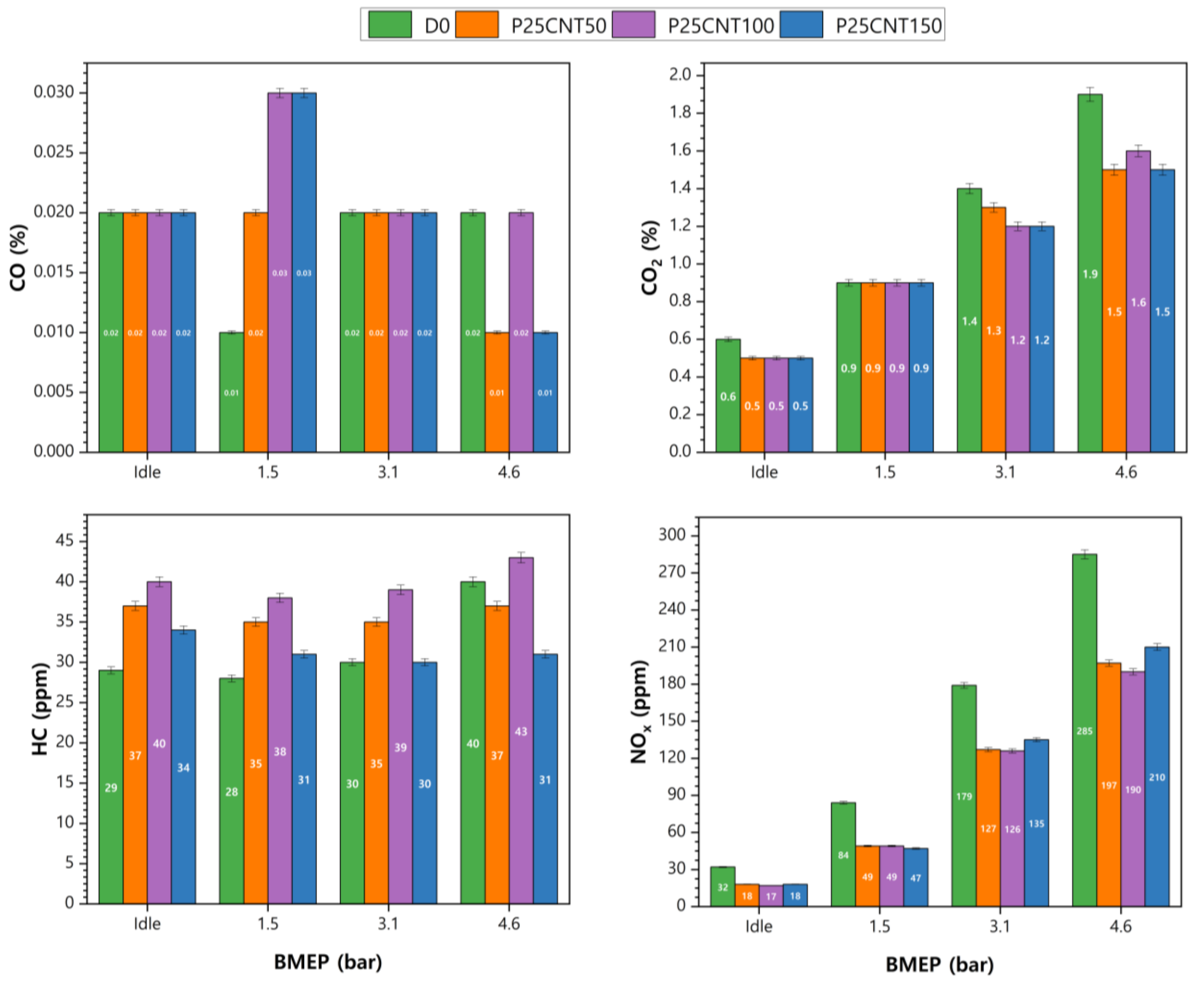

Figure 8. Variation of CO, CO_2, HC and NO_x emissions with engine load for D0 and MWCNT-propanol-diesel blends.

HC emission results revealed a notable trend where all MWCNT-enhanced propanol-diesel blends exhibited higher HC emissions, with an average of 8.2%, 26.7% and 14% for P25CNT50, P25CNT100 and P25CNT150, respectively compared to D0 fuel. This trend persisted across all load conditions, with the MWCNT blends consistently producing higher HC emissions than D0, peaking for P25CNT100 blend at maximum load. This increase is associated with several factors. First, propanol has a high latent heat of vaporization and lower volatility relative to D0, which reduced local mixture temperature during vaporization and promoted wall quenching, particularly near colder boundary layers. Second, the low cetane number of propanol delayed ignition, allowing more unburned or partially oxidized fuel to remain in near-wall regions. Although MWCNTs enhance heat transfer and support faster flame propagation, they can also promote localized cooling effects when agglomeration occurs [16], which further contributes to HC formation. The unfavorable trend is supported in the literature [23].

NO_x emissions results demonstrated a favorable trend where all MWCNT-enhanced propanol-diesel blends showed reductions in NO_x emissions compared to D0 fuel. The reductions were recorded as 40.7%, 42.4% and 38.3% for P25CNT50, P25CNT100, and P25CNT150, respectively, on average. At idle load, D0 produced higher NO_x, while all three MWCNT blends showed significant reductions. This beneficial trend became even more pronounced at higher loads, with reductions of 41-44% at 1.5 bar BMEP, 25-29% at 3.1 bar BMEP, and 26-31% at maximum load of 4.6 bar BMEP. The observed reduction in NO_x emissions from MWCNT-enhanced fuel blends resulted from several reasons. Although the MGT values of the MWCNT-enhanced blends increased, the NO_x emissions decreased. This behavior is linked to the localized thermal effects in the combustion chamber. The high thermal conductivity of MWCNTs promoted rapid heat redistribution, reducing localized hot spots where thermal NO_x typically forms. Thus, while the average in-cylinder temperature becomes higher, the peak flame temperatures were suppressed, leading to lower NO_x formation. Therefore, NO_x formation depends more strongly on localized peak flame temperatures than on the MGT, and the MWCNTs influence this spatial temperature distribution during combustion. The inverse relationship between NO_x emissions and propanol concentrations is corroborated by previous research [24]. The main finding of this study is that MWCNTs, due to their high thermal conductivity and catalytic surface characteristics, enhanced in-cylinder heat transfer and accelerated combustion kinetics, leading to improved BTE. At the same time, the improved heat distribution is expected to reduce localized high-temperature regions, thereby suppressing thermal NO_x formation. Therefore, the simultaneous improvement in efficiency and reduction in NO_x emissions is anticipated to result from the dual thermal and catalytic functions of MWCNTs in the propanol–diesel fuels. Table 5 shows the relative change in exhaust emissions of test fuels compared to D0.

Table 5. Relative change in exhaust emissions of test fuels compared to D0

Fuel Blend	CO (%vol) Change	CO_2 (%vol) Change	HC (ppm) Change	NOx (ppm) Change
P25CNT50	+ ~5–10%	− ~10–14%	+ ~8–12%	− ~35–40%
P25CNT100	+ ~12–18%	− ~15–18%	+ ~22–30%	− ~42–47%
P25CNT150	+ ~6–14%	− ~10–15%	+ ~12–18%	− ~38–44%

4 Conclusion

This study presents a systematic experimental evaluation of MWCNT-propanol-diesel blends in a compression ignition engine, addressing an existing research gap by examining the combined influence of propanol, diesel and MWCNTs on combustion, performance, and emission behavior. MWCNTs were incorporated into propanol-diesel blends at concentrations of 50, 100, and 150 ppm, designated as P25CNT50, P25CNT100, and P25CNT150, respectively. The experiments were conducted on a mono-cylinder, four-stroke, water-cooled, direct-injection compression ignition engine operating at a constant speed of 1500 rpm under four load conditions (idle, 1.5, 3.1, and 4.6 bar BMEP), with ultra-low sulfur diesel (D0) serving as the reference fuel.

The results revealed notable improvements in engine performance for MWCNT-enhanced blends. BTE increased significantly, showing average improvements of 8.8%, 11.1%, and 16% for P25CNT50, P25CNT100, and P25CNT150, respectively, compared to D0. BSFC also improved as P25CNT150 demonstrated a maximum reduction of 5.6%, while P25CNT100 and P25CNT50 exhibited a 1.4% reduction and a slight 0.6% increase, respectively. Combustion analysis indicated that MWCNT blends produced lower peak CPs. The peak HRRs were obtained higher. MGT was elevated in MWCNT blends. In addition, RoPR was moderated. Emissions showed that HC emissions increased for MWCNT-enhanced blends. In contrast, CO_2 emissions decreased by averages of 13.3%, 16.5% and, 18.7% for P25CNT50, P25CNT100, and P25CNT150, respectively. CO emissions slightly lower or at the same level. NO_x emissions were substantially reduced, with average decreases of 40.7%, 42.4% and 38.3% for P25CNT50, P25CNT100, and P25CNT150, respectively.

In conclusion, MWCNT-enhanced propanol-diesel blends demonstrate significant potential as sustainable diesel alternatives, offering improved BTE, better BSFC, and reduced CO_2 and NO_x emissions. These findings provide a foundation for the optimization of nanomaterial-assisted biofuels in compression ignition engines. Overall, the numerical trends indicate that MWCNTs support enhanced combustion kinetics but cannot fully offset the effects of propanol's lower cetane number and lower heating value. However, future studies should focus on optimizing the MWCNT concentration to avoid agglomeration effects, improving dispersion stability through the use of suitable surfactants, and adjusting the oxygenated fuel fraction to mitigate HC formation. In addition, the sustainability aspect of propanol–MWCNT–diesel blends could be strengthened by conducting a life-cycle or energy-chain assessment, which would determine the actual CO_2 reduction potential beyond engine-based emission measurements.

Similarity rate (iThenticate): 18%

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Nomenclature

Ag	Silver
Al	Aluminum
BMEP	Brake mean effective pressure
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
C	Carbon
CO	Carbon monoxide
CO_2	Carbon dioxide
CP	Cylinder pressure
D0	Ultra-low sulfur diesel
DTA	Differential thermal analysis
DTG	Derivative thermogravimetry
HC	Hydrocarbon
HRR	Heat release rate
MGT	Mean gas temperature
MWCNT	Multi-walled carbon nanotube
NO_x	Nitrogen oxides
P25CNT50	75% Diesel and 25% propanol with 50 ppm MWCNT
P25CNT100	75% Diesel and 25% propanol with 100 ppm MWCNT
P25CNT150	75% Diesel and 25% propanol with 150 ppm MWCNT
RoPR	Rate of pressure rise
SEM	Scanning electron microscope
TEM	Transmission electron microscopy
TG	Thermogravimetry
TGA	Thermogravimetric analysis