

Research Paper

Real-Time Surfactant-Free Emulsification of Plastic-Derived Diesel Oil: Combustion and Emission Characteristics

Wargiantoro Prabowo^{1,2}, Wira Jazair Yahya^{1,3}✉, Ahmad Muhsin Ithnin^{1,3}, Dhani Avianto Sugeng⁴, Trisno Anggoro², Frendy Rian Saputro^{1,2}, Erlan Rosyadi⁵

¹Advance Vehicle System, MJIT, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia

²Research Center for Energy Conversion Technology, National Research and Innovation Agency (BRIN), 625 Building, KST BJ Habibie, South Tangerang, 15314, Indonesia

³Institute for Sustainable Transport HiCOE, Universiti Teknologi Malaysia, Jalan Lengkok Kuasa, Johor Bahru, Malaysia

⁴Research Center for Transportation Technology, National Research and Innovation Agency (BRIN), 230 Building, KST BJ Habibie, South Tangerang, 15314, Indonesia

⁵Research Center for Fuel Technology, National Research and Innovation Agency (BRIN), 625 Building, KST BJ Habibie, South Tangerang, 15314, Indonesia

✉ wira@utm.my

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Abstract

Plastic waste pyrolysis has emerged as a promising strategy for converting non-recyclable plastics into plastic-derived diesel oil (PDDO), providing a pathway for both waste valorization and alternative fuel production. However, the direct utilization of PDDO in diesel engines remains constrained by suboptimal combustion behavior and elevated exhaust emissions. While real-time non-surfactant emulsion fuel supply systems (RTES) have been widely investigated for conventional diesel fuels, their application to PDDO has not yet been systematically evaluated in engine operation. This study presents the first implementation of a real-time non-surfactant emulsification system to generate surfactant-free water-in-PDDO emulsions containing 5–15% water by volume. Engine performance and exhaust emissions were experimentally assessed using a 4.5 kW single-cylinder compression-ignition generator at low and high loads. The results indicate that controlled water addition modifies combustion behavior by improving spray atomization and secondary droplet breakup associated with micro-explosion phenomena. Among the tested blends, the 15% water emulsion (EPO15) provided the most balanced performance, improving brake thermal efficiency by 6.48% while reducing NO_x emissions by up to 47.06% compared with the baseline fuel. Exhaust gas temperature was consistently reduced, without substantial deterioration in fuel consumption. These findings demonstrate that RTES can enhance the combustion and emission characteristics of PDDO, supporting its potential application in small-scale compression ignition engine systems.

Keywords: Plastic-derived diesel oil; Surfactant-free emulsion; Engine performance, Emissions; Waste-to-energy

1. Introduction

Global plastic production reached 400 million tonnes in 2022, generating approximately 267 million tonnes of plastic waste and contributing substantially to greenhouse gas emissions

throughout its lifecycle [1], [2], [3]. Beyond end-of-life management strategies such as landfilling and incineration, thermochemical conversion technologies have emerged as promising pathways for valorizing plastic waste into usable



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energy carriers. Among these, pyrolysis enables the production of plastic-derived diesel oil (PDDO), whose hydrocarbon distribution overlaps with those of gasoline, kerosene, and diesel [4], [5].

Despite its comparable calorific value (CV), the direct utilization of PDDO in compression ignition (CI) engines remains challenging. Variations in aromatic content, volatility, and molecular distribution can alter spray atomization, prolong ignition delay, and promote incomplete combustion, resulting in reduced brake thermal efficiency (BTE) and increased gaseous and particulate emissions relative to commercial diesel [6], [7]. Blending PDDO with diesel has been proposed as a mitigation strategy, with modest blending ratios (typically 10–20% v/v) reported to improve combustion characteristics and reduce selected emissions [8]. However, higher substitution levels often lead to deviations in viscosity, cetane number, and flash point beyond diesel standards, limiting large-scale substitution without engine modification or regulatory exemption [9], [10]. Consequently, advanced fuel-conditioning strategies are required to enhance PDDO combustion behavior while maintaining compatibility with existing diesel engines.

Water-in-diesel emulsification represents one such strategy. The dispersion of water within fuel droplets promotes secondary atomization via micro-explosions, improving air–fuel mixing and moderating peak combustion temperature [11]. Numerous studies have demonstrated reductions in NO_x and smoke emissions using surfactant-stabilized emulsions in diesel engines [12], [13]. Similar approaches applied to plastic-derived fuels have shown improvements in BTE and reductions in smoke and NO_x emissions [14]. However, conventional emulsification relies on chemical surfactants to maintain phase stability, which introduces additional costs, longer preparation time, storage constraints, and potential deposit formation in engine components [15], [16].

To address these limitations, real-time non-surfactant emulsion fuel supply systems (RTES) have been developed to generate emulsions on demand immediately prior to injection, eliminating the need for chemical stabilisers [17], [18]. Previous studies have demonstrated

performance improvements and emission reductions with RTES across various engine configurations using petroleum diesel, biodiesel, and blended fuels, as summarized in Table 1. However, the application of RTES to PDDO has not yet been systematically investigated under engine operating conditions. Moreover, no prior study has quantitatively compared the economic implications of surfactant-based emulsification and surfactant-free RTES for waste-derived fuels.

Given PDDO's distinct chemical composition, including elevated aromatic fractions and oxygenated compounds, its response to RTES-induced micro-explosion and temperature moderation may differ from that of conventional diesel. The absence of experimental validation and economic evaluation, therefore, represents a critical gap in the literature. Accordingly, this study investigates the combustion performance, emission characteristics, and economic feasibility of surfactant-free water-in-PDDO emulsions generated using a real-time emulsification system. Experiments were conducted on a 4.5 kW single-cylinder, direct-injection diesel engine under low- and high-load conditions representative of small-scale power generation applications. This engine type is widely used in household power generation and rural electrification applications, representing a practical target segment for plastic waste valorization technologies and RTES deployment in developing regions.

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Table 1. Summaries of RTES implementations on diesel engine generators

Test fuel ¹	Mixing method	Water content	Diesel engine specification	Performance ²	Emissions ²	Ref./year
W/D2-S/T/R	High shear and ultrasonic	5%	5 kW, 4-stroke, single cylinder, direct injection	BSFC ↓ BTE ↑	CO ↑; NOx ↓; PM ↓	[19]/2018
D2 and W/D2	High-pressure water mist injection, high shear, and ultrasonic mixing	5%	5 kW, capacity 0.4 L, 4-Stroke, direct injection, single cylinder, air-cooled	BSFC ↓ BTE ↑	CO ↑; NOx ↓; PM ↓	[20]/2018
W/B5	Ultrasonic with steam emulsification	5% and 10%	7 kW, capacity 0.5 L, single-cylinder, 4-stroke, water-cooled, direct injection	BSFC ↓ BTE ↑ EGT ↓	CO ↑; CO ₂ ↑; NOx ↓; PM ↓; UHC ↑	[21]/2020
D2 and W/D2	Circulation system	3%, 6%, and 9%	5 kW, capacity 0.4 L, 4-Stroke, single cylinder, direct injection, air-cooled	BSFC ↓ EGT ↓	CO ↑; NO ↓; PM ↓	[22]/2021
W/B10	High shear + static mixer	7 – 10%	6 kW, single cylinder, 4-stroke, direct injection	BSFC ↓ BTE ↑	CO ↑; NOx ↓	[23]/2023
D2 and W/D2	High shear + static mixer	3%, 6%, 9%, 15%, and 20%	92 kW, capacity 5.9 L, common rail direct injection, turbocharged, six cylinders in-line	BSFC ↓ BTE ↑ EGT ↓	CO ↑; NOx ↓; PM ↓	[24]/2023
D100 and W/PDDO	Circulation system + static mixer	5, 10, and 15	Diesel engine 4.5 kW, 4-Stroke, direct injection, single cylinder, air-cooled	Constant engine speed of 3100 rpm, 1 kW to 4 kW at intervals of 1 kW	To be determined	Present study

¹ S, T, R, BSFC, BTE, EGT, CO, CO₂, NOx, PM, and UHC denote seawater, tap water, rainwater, brake-specific fuel consumption, brake thermal efficiency, exhaust gas temperature, carbon monoxide, carbon dioxide, nitrogen oxides, particulate matter, and unburned hydrocarbon, respectively.

² The symbols (↑) and (↓) denote increases and reductions, respectively, observed in diesel engine studies relative to the base emulsion operating. These symbols are only for comparing results within the same research, not between different studies.

waste valorization technologies and RTES deployment in developing regions.

The contributions of this work are summarised as follows:

- Technical novelty: First systematic engine evaluation of real-time surfactant-free emulsification applied to PDDO.
- Experimental scope: Comparative assessment of BTE, BSFC, exhaust gas temperature, and regulated emissions across 5–15% water fractions under variable load conditions.
- Economic contribution: Quantitative cost comparison between conventional surfactant-stabilized emulsions and RTES-based emulsions for practical engine deployment.

This integrated technical and economic analysis aims to clarify the feasibility of RTES as a combustion-enhancement strategy for waste-derived plastic fuels in existing diesel engine platforms.

2. Methods

2.1. RTES Implementations on Diesel Engine Generators

In this study, five test fuels were prepared, including three surfactant-free emulsions produced using the RTES developed by RTES Technology (M) Sdn Bhd, Malaysia. The first was commercial diesel EURO 4 (D100), commercially obtained from a Pertamina fuel station in

Indonesia, and used as the base fuel. The second was PDDO obtained from the pyrolysis of municipal plastic waste at a processing facility in Banten, Indonesia, produced using a fixed-bed reactor operated at 320 °C for 6 hours. The condensed liquid fraction was filtered to remove residual solids prior to use as emulsion fuel. The third, fourth, and fifth were blends of PDDO with water at 5% (EPO5), 10% (EPO10), and 15% (EPO15) by volume, respectively. The EPO blends were generated using RTES configured as a closed-loop continuous recirculation circuit, as illustrated in Figure 1.

The total loop volume was approximately 0.35 litres and was constructed using HDPE tubing (outer diameters of 8 mm and 10 mm). A BOSCH FP 200 circulation pump with a flow rate of 140 L/h and a maximum pressure of 5 bar maintained continuous flow during engine operation. At the maximum circulation rate, the theoretical mean residence time within the RTES was approximately 9 s, calculated from the loop volume and rated volumetric flow, ensuring rapid renewal of the dispersed phase and limiting macroscopic stratification. A polypropylene static mixer (MA5.4-17S; inner diameter 5.4 mm; length 104 mm) was installed in the 10 mm section to enhance interfacial shear and promote droplet breakup. The static mixer enhanced interfacial shear and promoted droplet breakup through hydrodynamic mixing. The resulting shear conditions were consistent with those typically reported for continuous in-line water-in-oil emulsification systems, although the exact local shear rate was not directly measured.

Water was introduced via a calibrated OPTOS 3SM micro pump, with a volumetric accuracy of $\pm 0.3\%$, to regulate the volumetric fraction without interrupting base PDDO circulation. During

adjustments in engine load or water percentage, the main circulation pump remained continuously active, maintaining dynamic homogeneity within the loop, as illustrated in Figure 2. Consequently, no macroscopic phase separation was observed during steady engine operation. Prior to performance and emission measurements, EGT was monitored to ensure steady-state conditions; each fuel required approximately 10–15 min to achieve thermal stabilization before data acquisition.

Static stability was evaluated using a 15 mL graduated test tube (± 0.1 mL accuracy). The initial phase-separation times were 108 s, 51.43 s, and 33.82 s for EPO5, EPO10, and EPO15, respectively, based on more than 8 repeated observations per fuel, indicating reduced quiescent stability with increasing water fraction. However, under continuous RTES circulation, bulk phase separation was not observed due to ongoing shear-induced re-dispersion. Droplet size distribution and microscopic characterization were not quantified due to instrumental limitations; therefore, microscale dispersion characteristics were not directly measured. This limitation should be considered when interpreting the mechanistic role of droplet dynamics in the observed combustion and emission behavior.

2.2. Physicochemical Characterization

The physicochemical properties of D100 and PDDO were characterized prior to emulsification, and the results are summarized in Table 2. The evaluated parameters included CV, kinematic viscosity, density, flash point, distillation characteristics, cetane index, elemental composition (C, H, N), sulfur content, and hydrocarbon fraction distribution. The EPO

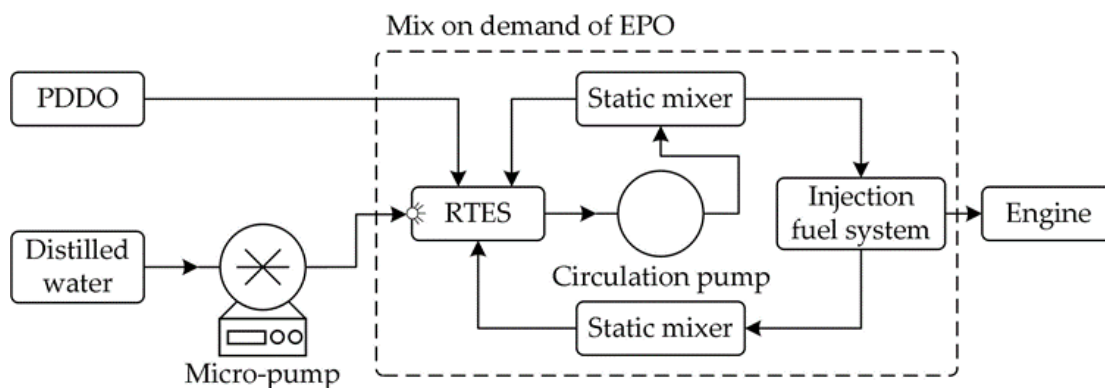


Figure 1. Schematic of EPO preparation

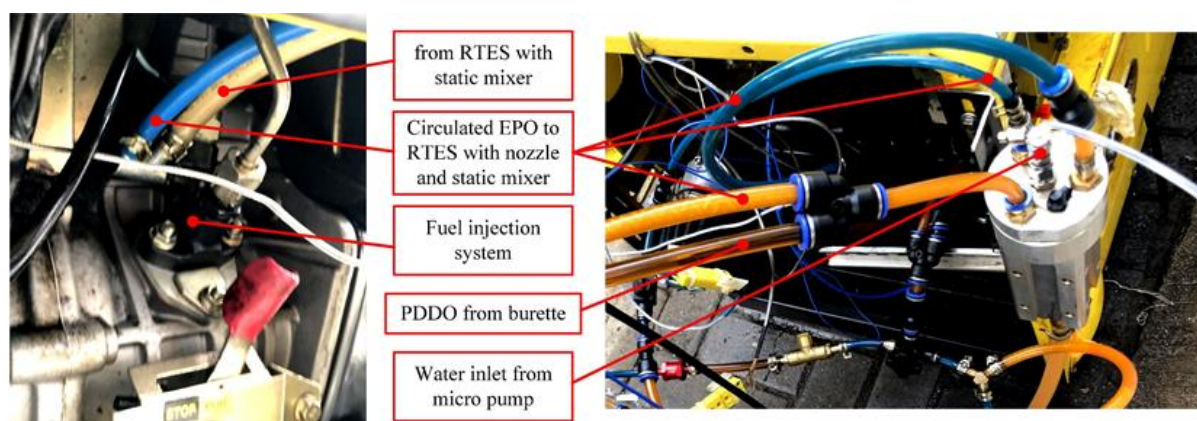


Figure 2. EPO preparation and circulation setup with a static mixer

Table 2. Properties of diesel and PDDO fuels tested

Properties	D100	PDDO	ASTM
Physical Analysis			
Caloric value [MJ/kg]	46.04	45.72	D5865
Kinematic viscosity [mm ² /s] at 40 °C	4.04	2.65	D445
Density [g/mL]	0.83	0.80	D4052
Flash point [°C]	75.50	33.77	D93
Pour point [°C]	0	18	D97
Sulfur content [ppm]	29.75	35.87	D4294
Cetane index	50	58.53	D4737
Ultimate Analysis			
Carbon, wt%	85.58	83.04	D5291
Hydrogen, wt%	13.91	13.72	D5291
Nitrogen, wt%	≤ 0.06	≤ 0.06	D5291
Ash, wt%	< 0.0010	0.0082	D482
Oxygen, wt%	0.41	3.18	D5291
Carbon Compound			
< C10	1.41	5.17	
C10 - C12	16.21	11.81	
C13 - C16	53.38	28.06	
C17 - C22	26.18	30.11	
> C22	2.82	24.90	

blends were not subjected to detailed physicochemical testing due to their rapid phase separation and thermodynamic instability under quiescent conditions, which could compromise representative sampling and analytical reproducibility.

The CV was determined using a Parr 6200 bomb calorimeter (isoperibol method). Kinematic viscosity was measured according to ASTM D445 using a LAUDA Viscotemp 18 system with temperature control via a LAUDA Eco Silver unit. Density at 15 °C was measured using an Anton Paar DMA 4500 M oscillating U-tube densitometer. Flash point was determined with a Miniflash FLP Touch (AMETEK Inc.) employing an electric arc ignition method. Distillation

characteristics were obtained following ASTM D86 procedures.

The cetane index was calculated using ASTM D4737 based on density at 15 °C and ASTM D86 distillation data, providing an indirect estimation of ignition quality appropriate for middle distillate fuels. The distillation profile of PDDO predominantly fell within the 180–360 °C boiling range, supporting its classification as a middle-distillate-type fraction, although compositional heterogeneity typical of plastic-derived pyrolysis oils may result in broader boiling distributions compared to petroleum diesel.

Elemental composition (C, H, and N) was measured using a LECO CHN628 analyzer (infrared detection for C and H; thermal

conductivity detection for N), while sulfur content was determined via X-ray fluorescence (Petra 4294) in accordance with ASTM D4294. The hydrocarbon fraction distribution of PDDO was analyzed by gas chromatography–mass spectrometry (Agilent 5977B GC/MSD) in full-scan mode (m/z 40–400) to identify compositional classes and molecular distributions. All measurements were conducted in triplicate, and the reported values represent arithmetic means to ensure analytical reliability.

2.3. Diesel Engine Testing

Performance and emission evaluations were conducted on the single-cylinder diesel engine specified in Table 3. The engine was directly coupled to a 4.5 kW alternator without an intermediate dynamometer, which was attached to a resistive load bank to simulate load conditions. Consequently, the reported BTE represents the overall engine-generator system efficiency based on electrical power output, rather than pure shaft-based engine efficiency. The experimental load range of 1–4 kW, corresponding to approximately 20–90% of the rated output, was selected to investigate low-to-high-load combustion behavior while avoiding prolonged operation at maximum rated power.

Figure 3 illustrates the schematic, while Figure 4 displays the actual setup. Fuel consumption was quantified using a 400 mL precision burette with ± 1 mL measurement accuracy. For D100 and

PDDO, FC was determined by timing a 5 mL fuel drop with a digital stopwatch with 0.01 s resolution. For EPO blends, FC was calculated based on the actual PDDO consumption, with corrections for water injection volumes supplied by a calibrated micropump ($\pm 0.3\%$ accuracy) to achieve the target blend ratios. In the present study, the micropump operated at a low supply pressure, sufficient only to ensure stable water delivery into the RTES. No direct high-pressure water injection into the combustion chamber was employed, and the diesel engine's original fuel injection pressure remained unmodified.

Exhaust gas sampling was conducted using a 300 mm stainless steel probe positioned at the exhaust outlet. The EGT thermocouple was installed 100 mm downstream from the cylinder exhaust port. Emission measurements were performed on a dry basis. The emission analyzer was calibrated prior to each experimental session in accordance with the manufacturer's guidelines.

The exhaust line was not thermally insulated, and testing was conducted under outdoor ambient conditions; therefore, steady-state operation was ensured by stabilizing EGT (± 5 °C) prior to data acquisition to minimize variability in emission readings. This stabilization threshold was adopted as an internal experimental criterion to ensure repeatable combustion and emission measurements. Ambient temperature was recorded during testing and incorporated into the uncertainty analysis.

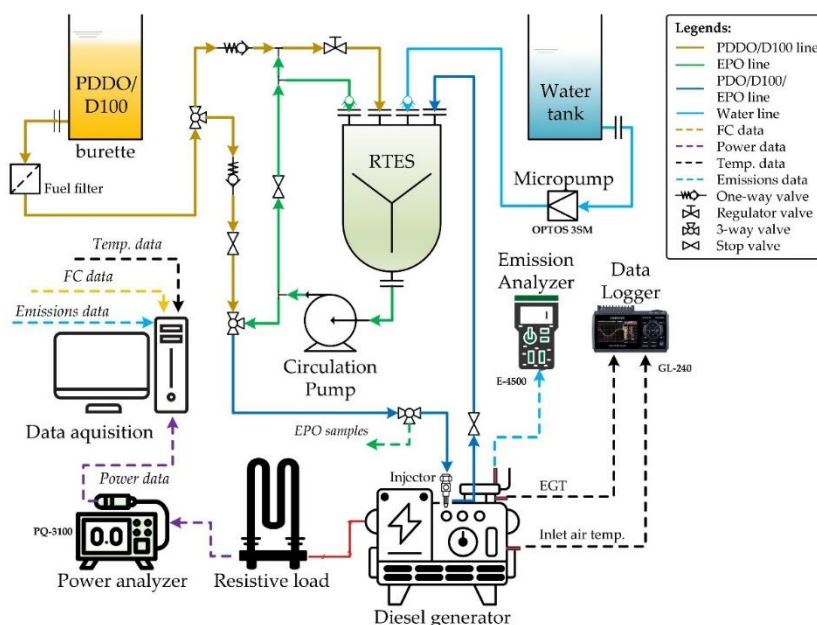
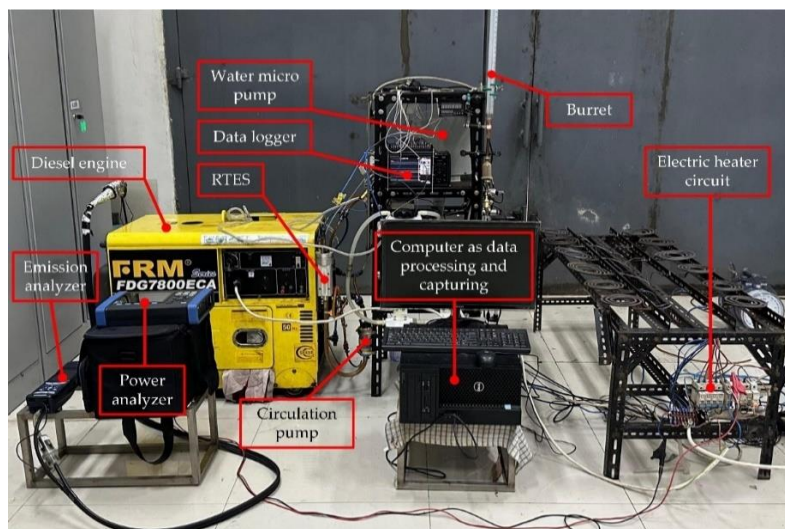


Figure 3. Schematic diagram for fuel testing on a diesel engine

Table 3. Specification of the test engine

Parameter	Specification
Maker/Model	Firman/FDG7800ECA
Engine type	186FA, Single cylinder, vertical, 4-stroke
Bore x Stroke (mm)	86 x 72
Compression ratio	18:1
Displacement (mL)	418
Injection timing (°BTDC)	19
Rated engine speed (rpm)	3000
Cooling system	Air-cooled
Combustion system	Direct injection
Alternator	Brush alternator
Rated output (kW)	4.5
Max output (kW)	5.0
Max torque (Nm @3000 rpm)	15.9
Fuel injection pressure (MPa)	20 (mechanical DI system)

**Figure 4.** Photograph of the experimental test setup

2.4. Data Collection and Uncertainty Analysis

Diesel engine performance was evaluated based on BSFC and BTE, which were calculated using Eq. (1) to Eq. (3).

$$BTE, (\%) = (P_a \times 3600 / (\dot{m}_f \times LCV)) \times 100 \quad (1)$$

$$BSFC, (g/kW \cdot h) = \dot{m}_f / P_a \quad (2)$$

$$\dot{m}_f, (g/h) = (\rho \times v_f / t_f) \times 3600 \quad (3)$$

where P_a is the measured real power output (kW), ρ is fuel density (g/ml), $\dot{m}_f$ is fuel flow rate (g/h), LCV is low CV (MJ/kg), v_f is the volume of fuel consumed (ml), and t_f is time to consume v_f in seconds.

The real electrical power output (kW) was measured using a Hioki PQ3100 power quality analyzer. As the engine was directly coupled to an

alternator and generator efficiency was not independently measured, the calculated BTE represents the combined engine-generator system efficiency rather than pure shaft-based engine efficiency. Electrical parameters, including voltage, current, and power factor (PF), were continuously monitored. Fuel consumption was determined using a graduated burette and stopwatch, and then converted to a mass flow rate using the known fuel density. The LHV of the fuel was used to represent the chemical energy input. Intake air temperature, EGT, and oil temperature were recorded using K-type thermocouples ($\pm 1\%$ accuracy) connected to a Graphtec GL840 data logger. Quantification of NO_x, CO, and CO₂ was performed using an E-4500 emission analyzer, with the technical specifications summarized in

Table 4.

Table 4. The equipment and instrumentation specifications

Parameters	Sensor/method	Resolution	Range	Accuracy
Power Quality Analyzer (Hioki PQ3100)				
Voltage (V)	L1000-5 Cord type	0.01	0 – 1000	±0.2%
Current (A)	CT7136AC Clamp type	0.001	0 – 50	±0.4% read; ±0.22% f.s.
Active power (W)	Calculated @ 200 ms	1	0 – 50000	±0.5% read; ±0.22% f.s.
Emission Analyzer (E4500)				
O ₂ (% vol)	Electrochemical	0.1	0 – 25	±0.2% vol
CO (ppm)	Electrochemical	1	0 – 400	±20 ppm
			401 – 4000	±5%
			4001 – 8000	±10%
NO (ppm)	Electrochemical	1	0 – 100	±5 ppm
			101 – 5000	±5%
CO ₂ (%)	Calculated	0.1% vol	0 – 99.9	-
Temperatures and Volumetric Flow				
EGT (°C)	Chromel	0.1	0 – 1000	±0.75%
Ambient temperature (°C)	Chromel	0.1	0 – 1000	±0.75%
FC (mL)	-	1	0 – 400	±0.25%
Micro-pump (mL/min)	Electromagnetic	0.01	0.01 – 20	±0.3%

The FC was measured with at least 20 data points per load condition for each repetition. Emission data were simultaneously recorded at 1-second intervals for 2 minutes, yielding 120 data points per test. EGT was continuously monitored as an indicator of engine stability before data acquisition to ensure steady-state operation. All tests were conducted at a consistent PF of 1.0, confirming purely resistive loading without reactive power interference. Each experimental set was repeated three times in accordance with ISO 8178-2:2008 and EPA 40 CFR Part 60, Subpart IIII. Mean values and corresponding standard deviations were calculated for each operating condition and fuel type. Error bars presented in the figures represent ±1 standard deviation, reflecting experimental repeatability.

Measurement uncertainties arose from instrument precision, repeatability, and environmental factors, notably ambient temperature, due to the outdoor setup. Emission uncertainties covered NO_x, CO, and CO₂, while performance uncertainties included active power, EGT, FC, ambient temperature (AT), and water content (WC) in EPO. The highest uncertainty for each parameter, as summarized in Table 5, was employed to estimate the overall uncertainty using Eq. (4) based on propagation-of-error analysis. The calculated overall uncertainty (U_{all}) was 3.24% representing the upper bound of

measurement deviation under the present experimental conditions. Observed differences exceeding the combined variability and propagated uncertainty range are interpreted as distinguishable within the experimental uncertainty bounds of the present setup. In contrast, variation below this threshold may fall within measurement tolerance. They should therefore be interpreted cautiously in comparative analyzes among D100, PDDO, and EPO fuels.

3. Results and Discussion

3.1. Brake Thermal Efficiency (BTE)

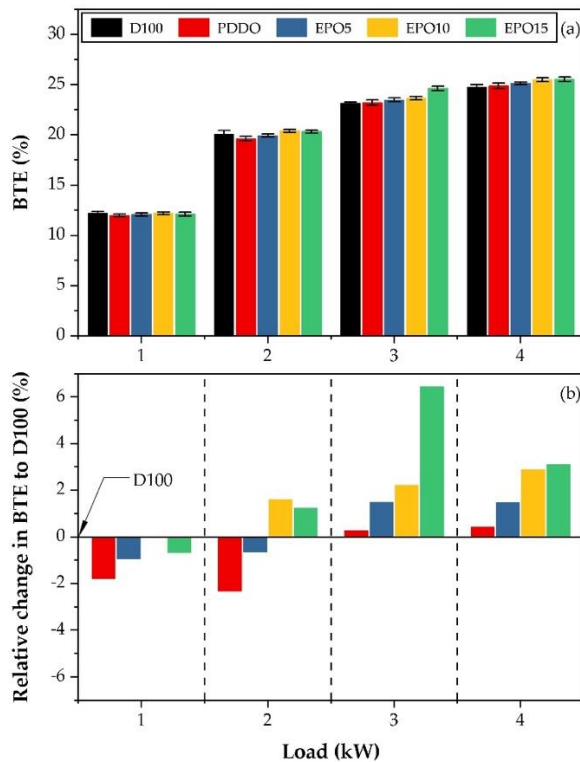
Figure 5 presents the variation of BTE of the engine-generator system as a function of load for all tested fuels. Unless otherwise stated, variations within the experimental uncertainty range (±3.24%) should be interpreted as functionally comparable and not indicative of statistically significant performance differences. For D100, BTE increased progressively with load, reflecting improved thermal utilization at elevated in-cylinder temperatures and a more complete fuel vaporization process [25].

PDDO exhibited a similar load-dependent trend. At a low load (1–2 kW), the BTE of PDDO was marginally lower than D100, while at higher loads (3–4 kW) the values became comparable. The observed differences across most operating conditions were minor and fell within

$$U_{all} (\%) = \sqrt{(U_{NOx}^2 + U_{CO}^2 + U_{CO2}^2 + U_{power}^2 + U_{EGT}^2 + U_{FC}^2 + U_{AT}^2 + U_{WC}^2)} \quad (4)$$

Table 5. The highest uncertainty values for a measured parameter

Parameters	Uncertainty
NO _x	0.88%
CO	0.58%
CO ₂	0.70%
Active power	0.03%
EGT	0.29%
Ambient temperature	2.42%
FC	0.41%
Micro-pump	0.46%

**Figure 5.** Variation of BTE for different fuels across various engine loads: (a) BTE values; (b) relative changes compared to D100

measurement tolerance, indicating broadly similar system-level efficiency. The slight reduction at low load may be associated with its lower flash point, CV, and density, which can influence mixture preparation under low-temperature combustion conditions [26], [27]. Furthermore, the significantly higher oxygen content in PDDO (approximately 7.7 times that of D100) may contribute to excessively lean air-fuel mixtures during the premixed combustion phase, thereby reducing thermal efficiency [28], [29]. At higher loads, increased in-cylinder pressures and temperatures likely mitigated these effects by enhancing vaporization and oxidation of PDDO [30].

The EPO blends exhibited an overall improvement in BTE compared to D100. At a low load, variation relative to D100 was minor. In contrast, at high load, particularly at 3 kW, EPO15 exhibited a 6.48% increase in BTE compared with D100. The improvements are primarily ascribed to the micro-explosion phenomenon, in which the vaporization of dispersed water droplets within the emulsion induces secondary atomization, resulting in a finer fuel spray distribution and improved air-fuel mixing [31]. The effect is further intensified at elevated cylinder pressures and temperatures, as reported by Mohd Tamam *et al.* and Mondal and Mandal, leading to more complete combustion and improved thermal efficiency [32], [33].

The efficiency behavior reflects the interaction of two competing mechanisms: (i) enhanced atomization and combustion completeness due to micro-explosion phenomena, and (ii) the endothermic cooling effect associated with water vaporization. At lower loads, where cylinder temperature is limited, the cooling effect may offset atomization benefits, particularly at lower water fractions (EPO5). At higher loads, the elevated thermal environment enables secondary atomization without excessive quenching, allowing mid- to higher-water fractions (EPO10–EPO15) to yield net efficiency gains.

In summary, the results indicate that water-in-PDDO emulsification can improve BTE under medium-to-high load conditions, particularly at higher water fractions. The most pronounced improvement was observed for EPO15 at 3 kW, exceeding the experimental uncertainty threshold. While performance gains are load-dependent and governed by the balance between secondary atomization and evaporative cooling, the findings demonstrate the practical viability and cost-efficiency of real-time, surfactant-free emulsification methods for advancing the application of plastic-derived fuels in compression-ignition engines. Nevertheless, the overall benefit must be evaluated alongside emission behavior and system-level considerations.

3.2. Brake-Specific Fuel Consumption (BSFC)

Figure 6 illustrates the variations in BSFC and relative changes for different fuel types at various engine loads. For D100, BSFC decreased significantly

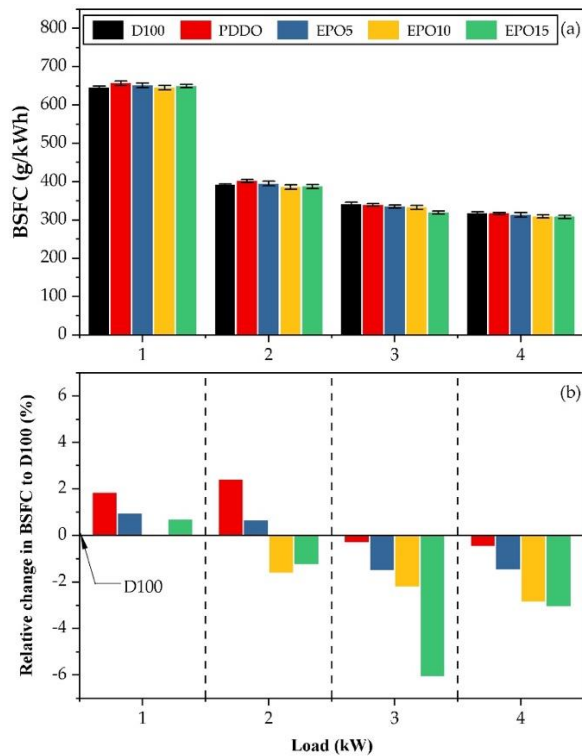


Figure 6. Variation of BSFC for different fuels across various engine loads: (a) BSFC values; (b) relative changes compared to D100

with increasing load, reflecting improved BTE and reduced relative heat losses. PDDO exhibited a similar load-dependent trend. At low load, its BSFC was marginally higher than D100, which can be attributed to its lower density and CV [30]. These properties require a greater fuel mass to maintain the same power output [6], [34], [35]. However, the differences between PDDO and D100 across most load conditions remained within the overall experimental uncertainty, indicating comparable fuel economy performance within measurement tolerance. At higher loads, improved in-cylinder evaporation and oxidation mitigated physicochemical constraints, resulting in BSFC values closely aligned with those of D100 [36]. This behavior is consistent with the near-equivalent BTE observed at elevated load conditions.

For EPO blends, BSFC behavior mirrored the BTE trends described in Section 3.1. At low loads, variations relative to D100 were minimal. In contrast, at medium-to-high loads, EPO15 exhibited a clear reduction in BSFC, indicating improved fuel utilization. This reduction corresponds directly to the enhanced BTE observed under the same operating conditions

and reflects more effective conversion of chemical energy into useful electrical output.

The improved fuel economy at higher loads is attributed to enhanced atomization and air-fuel mixing induced by rapid vaporization of dispersed water droplets within the emulsion [32]. This process subsequently accelerates evaporation and oxidation, thereby reducing ignition delay. Additionally, the latent heat of water vaporization cools the intake charge, shifting the peak of heat release closer to top dead center (TDC), thereby enhancing indicated efficiency and reducing heat losses [37], [38]. In contrast, at lower loads, limited thermal energy restricts effective secondary atomization, and the evaporative cooling effect of water can offset potential efficiency gains, leading to negligible net change in BSFC [32], [39], [40].

Overall, the BSFC results are thermodynamically consistent with the BTE findings. The interaction among CV, density, water content, engine load, and combustion temperature determines evaporation dynamics and burn rates, leading to nonlinear BSFC trends across the load spectrum. These results emphasize that efficiency improvements in EPO emulsions are primarily realized at medium-to-high load, where favorable thermal conditions enable net combustion improvements.

3.3. Exhaust Gas Temperature (EGT)

Figure 7 shows the EGT and its relative variations for different fuel types across a range of engine loads. EGT increases consistently with increasing engine loads for all fuels, with PDDO exhibiting the highest values. In contrast, as the water content in EPO blends increases, the EGT systematically decreases, reaching values below D100 at higher loads. At low loads (1–2 kW), both PDDO and EPO blends show higher EGT than D100, with PDDO exceeding D100 by 7.17% at 1 kW. This result is attributed to slightly delayed combustion and a prolonged oxidation phase due to the higher oxygen content (3.18 wt%) compared to D100 (0.41 wt%), although PDDO's higher CI, which tends to elevate post-flame gas temperature in low-load conditions [6]. Furthermore, the lower viscosity and flash point of PDDO potentially promote longer ignition delay, leading to a more intense heat release rate (HRR) after the start of combustion (SoC) [41], [42]. Combined with its chemical composition, which is rich in alkane

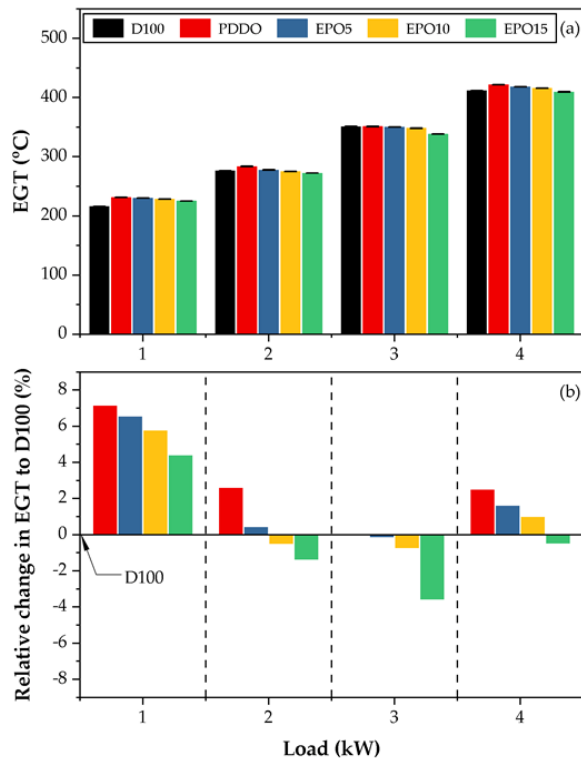


Figure 7. Variation of EGT for different fuels across various engine loads: (a) EGT values; (b) relative changes compared to D100

compounds possessing stronger molecular bonds and higher structural compactness than those in D100 [41], [43], this results in a greater chemical energy contribution during the late oxidation phase, thereby raising exhaust temperatures [44], [45]. Interestingly, EPO15 results in a relatively lower increase of 4.42%, indicating that higher water content in EPO begins to moderate combustion temperature, likely through micro-explosions or improved atomization. Previous studies also indicate that water molecules dispersed with plastic oil in the combustion chamber increase ignition delay and reduce the HRR, resulting in lower EGT than with D100 [46].

At higher loads (3–4 kW), the trend intensifies, where EPO10 and EPO15 produce even lower EGT than D100, with EPO15 achieving a maximum reduction of 3.63% at 3 kW. Notably, EPO15 achieved the highest BTE and the lowest BSFC among all tested fuels despite exhibiting the lowest EGT at high loads. This decoupling between EGT and BTE suggests more complete combustion and reduced thermal energy loss [47], [48]. Furthermore, this reduction is due to microexplosions from water droplets, which promote fuel atomization and result in more

uniform combustion [22], [32]. The latent heat absorption associated with water vaporization introduces a heat sink effect, suppressing peak in-cylinder temperatures and lowering EGT [49].

3.4. NO_x Emissions

Figure 8 presents the NO_x emissions and their variation with engine load for different fuel types. For all fuels, NO_x increased steadily with load, reflecting the well-established dependence of thermal NO_x formation on combustion temperature and heat release intensity. D100 exhibited the highest NO_x concentrations, rising from 171.57 ppm at 1 kW load to 612.92 ppm at 4 kW load. PDDO consistently produced lower NO_x emissions across the load range, with reductions of up to 21.38% at low load. This behavior may be associated with differences in combustion characteristics arising from its oxygenated compounds, such as alcohols, ketones, and esters, which can promote more distributed heat release and reduce localized high-temperature zones [41], [49].

The EPO blends demonstrated more pronounced NO_x mitigation, particularly at low load. At 1 kW, EPO15 achieved the largest

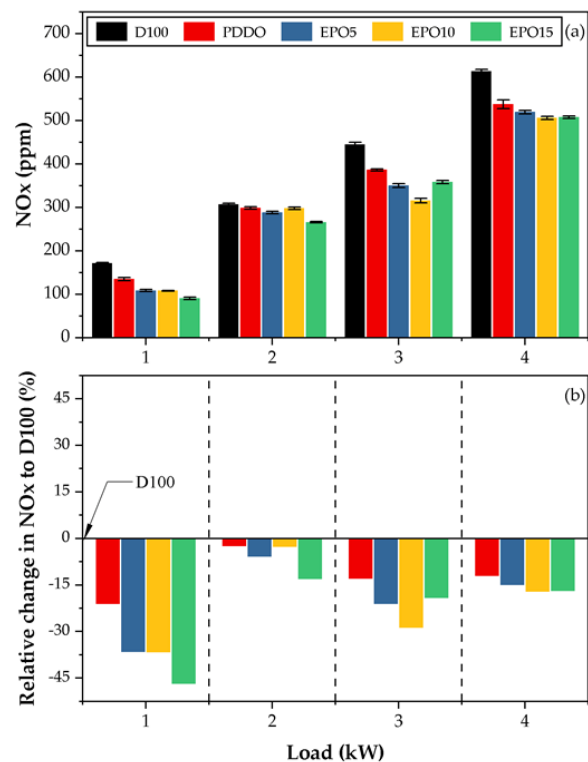


Figure 8. NO_x emissions for different fuels across various engine loads: (a) NO_x values; (b) relative changes compared to D100

reduction of 47.06% relative to D100. The reduction is primarily attributed to the presence of dispersed water within the emulsion. During combustion, water vaporization absorbs latent heat and acts as a thermal buffer, moderating peak combustion temperature and suppressing thermal NO_x formation [46], [50]. According to the Zel'dovich thermal mechanism, NO_x formation accelerates rapidly when in-cylinder temperatures exceed approximately 1800 K [51]. Although in-cylinder temperature was not directly measured in this study, the lower EGT observed at higher water fractions suggests a reduction in overall thermal intensity. Since EGT represents post-combustion exhaust temperature rather than peak flame temperature, this mechanism is interpreted qualitatively.

As engine load increases, the magnitude of NO_x reduction decreased but remained evident, indicating that elevated combustion temperature and pressure partially counteract the thermal buffering effect of water [52]. In addition to bulk thermal moderation, dispersed water may influence local combustion dynamics. Rapid vaporization can alter the development of transient heat release and the temperature gradients within the reaction zone, particularly under low-load conditions where thermal intensity is limited [47]. At higher loads, increased thermal energy reduces the relative dominance of this cooling mechanism, and higher water content may influence ignition behavior and combustion phasing. Under certain conditions, extended ignition delay can increase the premixed heat release fraction, potentially generating localized high-temperature regions despite overall cooling effects [29], [53]. Overall, the NO_x trends align with the corresponding efficiency and exhaust temperature behavior, indicating thermally coherent combustion characteristics across the tested load range.

3.5. CO Emissions

Figure 9 illustrates the variation of CO emissions across different engine loads for all tested fuels. For both D100 and PDDO, CO emissions consistently decreased with increasing load, indicating improved oxidation of CO to CO₂ under elevated conditions, thereby lowering CO formation [7], [54]. Compared with D100, PDDO exhibited marginally higher CO at low load but

achieved reductions at medium-to-high loads, reaching approximately 18.78% lower CO at 4 kW. This behavior is consistent with improved oxidation efficiency at higher combustion temperature and aligns with the comparable BTE observed under elevated loads [31].

In contrast, all EPO blends exhibited higher CO emissions than D100, particularly at low loads. At 1 kW, CO increased by 34.20%, 37.17%, and 43.85% were observed for EPO5, EPO10, and EPO15, respectively. These findings indicate incomplete oxidation under limited thermal conditions, where the evaporative cooling effect of water reduces effective combustion temperature [10], [55]. Although secondary atomization may enhance spray dispersion, insufficient thermal intensity at low loadings can limit CO-to-CO₂ conversion, leading to elevated CO levels [20], [56].

At higher loads, CO emissions continued to rise with increasing water content. At 4 kW, EPO15 showed a 63.07% increase relative to D100, while low water addition (EPO5) resulted in CO levels comparable to those of D100. These results suggest that excessive water content shifts the balance toward thermal dilution rather than

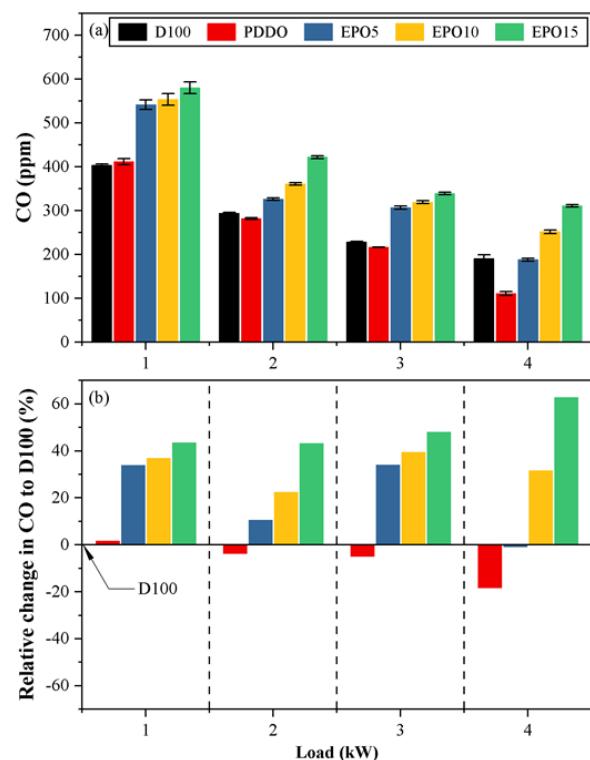


Figure 9. CO emissions for different fuels across various engine loads: (a) CO values; (b) relative changes compared to D100

oxidation enhancement [57]. Overall, the CO behavior indicates a trade-off between temperature moderation and complete oxidation, highlighting the importance of optimizing water fraction to maintain favorable efficiency without increasing incomplete combustion products [27], [57].

When considered together with the efficiency results, the data indicate a load-independent optimization requirement. While higher water content (EPO15) enhances BTE and reduces NO_x at medium-to-high loads, it may incur CO penalties due to incomplete oxidation. Conversely, moderate water addition (EPO5 – EPO10) provides a more balanced performance at higher loads, maintaining efficiency improvements with comparatively lower CO increase. At low loads, the thermal limitations reduce the benefit of higher water contents, suggesting that optimal water content is strongly dependent on engine load and operating temperature [32].

3.6. CO₂ Emissions

Figure 10 illustrates the CO₂ emission behavior of various fuels under varying engine load conditions. For all fuels, CO₂ increased with load, reflecting enhanced overall carbon oxidation at higher combustion temperatures and improved thermal conditions. D100 exhibited an increase from 3.09% at 1 kW to 5.60% at 4 kW. PDDO produced slightly higher CO₂ at low loads, with increases of 7.67% at 1 kW and 5.26% at 2 kW relative to D100. This behavior is consistent with improved early-stage oxidation under elevated thermal intensity, as also reflected in the corresponding EGT trends. However, at higher loads, CO₂ emissions from PDDO became comparable to those from D100, indicating similar overall oxidation efficiency under diffusion-dominated combustion conditions. In addition, the longer ignition delay of PDDO causes delayed combustion phasing at high loads, reducing the time available for complete oxidation before the exhaust phase [42].

The EPO blends exhibited a load- and water-fraction-dependent CO₂ emission response. At low load, EPO5 showed the highest CO₂ increase, with a 16.69% increase at 1 kW, indicating enhanced combustion efficiency driven by the micro-explosion phenomenon, which promoted

secondary atomization and improved air-fuel mixing [32], [58]. Increasing water content to 10% and 15% reduces this enhancement, because excessive thermal dilution can offset the benefits of secondary atomization. Conversely, at 2 kW, EPO15 unexpectedly showed a 9.43% increase in CO₂ emissions, likely due to the onset of more vigorous micro-explosions triggered by higher in-cylinder temperatures, which allowed for better evaporation and combustion of water-fuel droplets [31], [59]. At high loads, EPO5 and EPO10 exhibited greater CO₂ emissions than D100, with EPO10 showing the highest increase of 10.42% at 3 kW and 3.75% at 4 kW. This trend reflects the balance between improved mixture formation and the cooling effect introduced by higher water content [42], [56].

In contrast, EPO15 produced CO₂ emissions comparable to those of D100 at high loads, indicating that excessive water addition may reduce overall oxidation completeness under certain conditions, consistent with the CO trends discussed. Overall, the CO₂ results confirm that carbon oxidation efficiency is governed by the interplay between atomization enhancement and thermal moderation. Optimal water content,

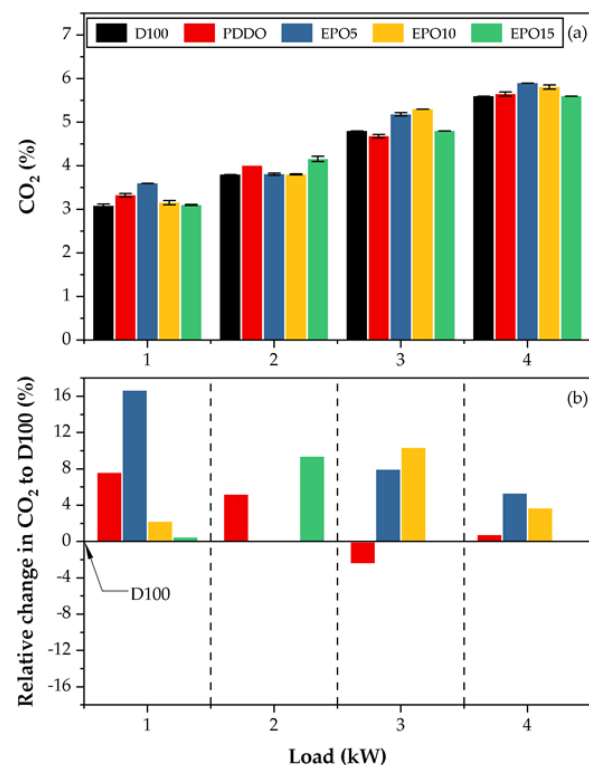


Figure 10. CO₂ emissions for different fuels across various engine loads: (a) CO₂ values; (b) relative changes compared to D100

therefore, depends on engine load, where moderate water fractions may enhance oxidation at sufficient thermal intensity, while excessive dilution can limit complete conversion of CO to CO₂ [60].

3.7. Comparative Analysis

Table 6 summarizes the relative changes in engine performance and emission parameters for surfactant-free EPO blends compared with D100 and PDDO across all load conditions. Positive and negative values indicate increases and reductions, respectively, compared to the baseline fuels. The values in bold indicate the best performance for each combination of water-in-PDDO emulsion fuel. Values in parentheses denote engine load (kW).

3.8. Cost Analysis

A simplified techno-economic comparison was conducted to evaluate the variable operating costs associated with the different formulations, with emphasis on fuel and surfactant expenses as the dominant controllable parameters under laboratory-scale conditions. Diesel pricing was referenced to the standard Pertamina retail rate in Indonesia, whereas the PDDO price represents an estimated local production cost for plastic pyrolysis oil under small-scale processing conditions. Surfactant prices were sourced from current Alibaba.com listings. It should be noted that these values represent indicative market-based inputs and may vary by region and scale.

Fuel cost per kWh was calculated based on measured BTE and corresponding fuel consumption at a 4 kW load, providing a performance-normalized economic comparison. The BTE of batch emulsion with 15% water was estimated at 26.06% via linear interpolation from reported literature data at 10% and 20% water content, ensuring a realistic performance measure [61]. While this interpolation provides a reasonable approximation for comparative purposes, it introduces uncertainty. It should not be interpreted as an experimentally validated value under the present test conditions.

As summarized in **Table 7**, the RTES emulsion achieved the lowest fuel cost per kWh, among the evaluated formulations, outperforming diesel and batch-emulsified fuel, and remaining slightly more economical than neat PDDO. The cost advantage of RTES arises from two interacting factors: (i) improved combustion efficiency relative to neat PDDO, and (ii) elimination of surfactant cost required in batch emulsification.

In contrast, although batch emulsions exhibit higher interpolated BTE, the additional surfactant cost offsets the efficiency gain, resulting in the highest cost per kWh among the evaluated fuels. This result demonstrates that combustion improvement alone does not guarantee economic advantage unless chemical additive costs are minimized.

A sensitivity analysis indicates that the economic ranking is primarily influenced by three parameters: the fuel price differential (diesel vs

Table 6. Comparative average changes in engine performance and emissions for EPO blends relative to D100 and PDDO

Parameter	Relative to D100 (%)			Relative to PDDO (%)		
	EPO5	EPO10	EPO15	EPO5	EPO10	EPO15
Low load (1-2 kW)						
BTE	-0.70 (2)	+1.64 (2)	+1.27 (2)	+1.71 (2)	+4.11 (2)	+3.73 (2)
BSFC	+0.70 (2)	-1.62 (2)	-1.26 (2)	-1.68 (2)	-3.95 (2)	-3.60 (2)
EGT	+0.47 (2)	-0.54 (2)	-1.43 (2)	-2.11 (2)	-3.09 (2)	-3.96 (2)
NOx	-36.85 (1)	-36.98 (1)	-47.06 (1)	-19.67 (1)	-19.84 (1)	-32.66 (1)
CO	+10.91 (2)	+22.75 (2)	+43.55 (2)	+15.72 (2)	+28.07 (2)	+40.99 (1)
CO ₂	+0.18 (2)	+0.04 (2)	+0.54 (1)	-4.83 (2)	-5.02 (1)	-6.62 (1)
High load (3-4 kW)						
BTE	+1.53 (3)	+2.94 (4)	+6.48 (3)	+1.21 (3)	+2.47 (4)	+6.15 (3)
BSFC	-1.50 (3)	-2.85 (4)	-6.08 (3)	-1.20 (3)	-2.41 (4)	-5.79 (3)
EGT	-0.19 (3)	-0.77 (3)	-3.63 (3)	-0.87 (4)	-1.47 (4)	-3.69 (3)
NOx	-21.32 (3)	-29.04 (3)	-19.44 (3)	-9.37 (3)	-18.26 (3)	-7.20 (3)
CO	-1.29 (4)	+32.02 (4)	+63.07 (4)	+21.54 (4)	+47.63 (3)	+56.75 (3)
CO ₂	+5.36 (4)	+3.75 (4)	0.00 (4)	+4.52 (4)	+2.92 (4)	-0.80 (4)

Table 7. Cost comparison of fuel and surfactants for different emulsification methods

Parameter	Diesel (D100)	PDDO	Batch Emulsion (PDDO+ Surfactant)	RTES Emulsion (PDDO+15% water, Surfactant-free)
Fuel cost per liter (\$)	0.84	0.54	0.91	0.54
Surfactant cost per liter (\$)	0.00	0.00	0.37	0.00
Brake Thermal Efficiency (%)	24.76	24.87	26.06	25.54
Fuel consumption per kWh (liter)	4.04	4.02	3.84	3.92
Fuel cost per kWh (\$)	3.38	2.18	3.49	2.12
Total operational cost per hour, 4 kW load (\$)	13.51	8.71	13.97	8.48

PDDO) [62], achievable BTE at different water fractions [63], and surfactant cost [17]. For example, a modest $\pm 2\%$ variation in BTE would proportionally affect fuel consumption per kWh, potentially narrowing the cost gap between RTES and neat PDDO. Similarly, fluctuations in crude oil-derived diesel pricing would significantly alter comparative cost advantages. Therefore, the present analysis should be interpreted as condition-specific rather than universally generalizable.

It is further emphasized that this evaluation focuses on variable fuel-related costs and does not incorporate system-level expenses such as long-term injector wear, maintenance, mixing energy consumption, capital investment for RTES hardware, or lifecycle environmental costs. Consequently, the findings represent a comparative laboratory-scale operating cost assessment rather than a full commercial techno-economic feasibility study. Nevertheless, within the defined boundary conditions, eliminating surfactants and achieving measurable efficiency improvements provides a clear variable-cost advantage for RTES-based emulsification under high-load operation.

4. Conclusion

This study evaluated the application of a real-time surfactant-free emulsification system (RTES) for producing water-in-plastic-derived diesel oil (PDDO) emulsions and assessed their technical and economic feasibility in small-scale diesel engines.

From a performance perspective, controlled water addition improved combustion behavior, particularly at moderate-to-high loads. The 15% water emulsion (EPO15) achieved the most favorable balance, increasing the BTE by up to 6.48% without imposing significant fuel

consumption penalties. These improvements indicate enhanced spray atomization and secondary droplet breakup associated with micro-explosion phenomena, contributing to more effective air-fuel mixing and complete combustion relative to neat PDDO under comparable load conditions.

In terms of emissions, substantial NO_x mitigation was observed, with reductions of up to 47.06% relative to baseline diesel operation. The exhaust gas temperature was consistently moderated across loads. However, the increase in CO emissions at low load highlights a trade-off between temperature and oxidation, indicating that the optimal water fraction depends on the engine operating regime.

From an economic standpoint, eliminating chemical surfactants through RTES reduces the preparation complexity and associated material costs compared with conventional batch emulsification. The combined technical and cost evaluations support the feasibility of RTES for decentralised diesel generator applications utilizing plastic-derived fuels.

Overall, this study demonstrated that real-time surfactant-free emulsification can enhance the combustion efficiency and emission characteristics of PDDO without requiring engine hardware modification. Nevertheless, long-term durability, injector deposit formation, and full operational lifecycle impacts were not examined and remain critical considerations prior to large-scale deployment.

Future work should focus on the multi-objective optimization of the water fraction across varying engine loads using response surface methodology to define a robust performance-emission operating window. Extended endurance testing and life cycle economic assessments are necessary to validate the long-term reliability and commercial scalability of the proposed system.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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References

- [1] *Global Waste Management Outlook 2024 - Beyond an age of waste: Turning rubbish into a resource*. United Nations Environment Programme, 2024. doi: 10.59117/20.500.11822/44939.
- [2] K. Houssini, J. Li, and Q. Tan, "Complexities of the global plastics supply chain revealed in a trade-linked material flow analysis," *Communications Earth & Environment*, vol. 6, no. 1, p. 257, Apr. 2025, doi: 10.1038/s43247-025-02169-5.
- [3] P. M. Forster *et al.*, "Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence," *Earth System Science Data*, vol. 16, no. 6, pp. 2625–2658, Jun. 2024, doi: 10.5194/essd-16-2625-2024.
- [4] I. U. Eze, O. O. Okwonna, G. W. Komi, A. I. Hart, and I. Vincent-Akpu, "Comparative Analysis of Kerosene Grade Fuel from Pyrolysis of HDPE and LDPE Waste Plastics," *Journal of Engineering Research and Reports*, vol. 26, no. 2, pp. 1–13, Jan. 2024, doi: 10.9734/jerr/2024/v26i21068.
- [5] M. H. Rahman, P. R. Bhoi, and P. L. Menezes, "Pyrolysis of waste plastics into fuels and chemicals: A review," *Renewable and Sustainable Energy Reviews*, vol. 188, p. 113799, Dec. 2023, doi: 10.1016/j.rser.2023.113799.
- [6] S. Pal *et al.*, "Experimental evaluation of diesel blends mixed with municipal plastic waste pyrolysis oil on performance and emission characteristics of CI engine," *Case Studies in Thermal Engineering*, vol. 47, p. 103074, Jul. 2023, doi: 10.1016/j.csite.2023.103074.
- [7] A. Pumpuang, N. Klinkaew, K. Wathakit, A. Sukhom, and E. Sukjit, "The influence of plastic pyrolysis oil on fuel lubricity and diesel engine performance," *RSC Advances*, vol. 14, no. 14, pp. 10070–10087, 2024, doi: 10.1039/D3RA08150H.
- [8] B. Alawa and S. Chakma, "Experimental Investigation in Compression Ratio on Performance, Combustion and Emission of VCR Engine using Pyrolysis-oil Produced from Waste Plastic Materials," *Materials Today: Proceedings*, vol. 72, pp. 2593–2609, 2023, doi: 10.1016/j.matpr.2022.07.228.
- [9] P. Singh Gautam, A. Partap Singh, S. Chand, and A. Sehgal, "Combustion knocking intensity behavior analysis using wavelet approach and optimizing water-emulsified diesel fuel: Engine combustion, performance and emission analysis with novel surfactants," *Fuel*, vol. 391, no. February, p. 134656, 2025, doi: 10.1016/j.fuel.2025.134656.
- [10] A. K. Hasannuddin *et al.*, "Effect of emulsion fuel on engine emissions—A review," *Clean Technologies and Environmental Policy*, vol. 18, no. 1, pp. 17–32, Jan. 2016, doi: 10.1007/s10098-015-0986-x.
- [11] P. Murugesan *et al.*, "Exploration of low heat rejection engine characteristics powered with carbon nanotubes-added waste plastic pyrolysis oil," *Process Safety and Environmental Protection*, vol. 176, pp. 1101–1119, Aug. 2023, doi: 10.1016/j.psep.2023.06.051.
- [12] R. Vigneswaran, D. Balasubramanian, and B. D. S. Sastha, "Performance, emission and combustion characteristics of unmodified diesel engine with titanium dioxide (TiO₂) nano particle along with water-in-diesel emulsion fuel," *Fuel*, vol. 285, p. 119115, Feb. 2021, doi: 10.1016/j.fuel.2020.119115.

- [13] M. R. Seifi *et al.*, "Statistical evaluation of the effect of water percentage in water-diesel emulsion on the engine performance and exhaust emission parameters," *Energy*, vol. 180, pp. 797–806, Aug. 2019, doi: 10.1016/j.energy.2019.04.093.
- [14] S. Gowrishankar and A. Krishnasamy, "Emulsification – A promising approach to improve performance and reduce exhaust emissions of a biodiesel fuelled light-duty diesel engine," *Energy*, vol. 263, p. 125782, Jan. 2023, doi: 10.1016/j.energy.2022.125782.
- [15] R. P. Singh and P. S. Gautam, "Predictive modeling and multi-objective optimization of CI engine performance, combustion and emissions parameters with water-emulsified diesel using SVR and SHO," *Biomass and Bioenergy*, vol. 208, p. 108818, May 2026, doi: 10.1016/j.biombioe.2025.108818.
- [16] S. A. A. Kashinath, H. Hashim, N. A. Yunus, and A. A. Mustaffa, "Design of surfactant for water in diesel emulsion fuel for designing eco-friendly fuel," *Chemical Engineering Transactions*, vol. 63, pp. 433–438, 2018, doi: 10.3303/CET1863073.
- [17] Md Mujibur Rahman, Wira Jazair Yahya, Hasannuddin Abd Kadir, Ahmad Muhsin Ithnin, Qayyum Mohd Tamam, and Hasbullah Abdul Rahman, "Comparison of Diesel Engine Performance between a Mechanical Pump and a Common Rail Fuel Injection System Equipped with Real-Time Non-Surfactant Emulsion Fuel Supply System," *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, vol. 91, no. 2, pp. 41–50, Feb. 2022, doi: 10.37934/arfmts.91.2.4150.
- [18] W. N. I. Wan Mahdi *et al.*, "Effect of Electrical Load On the Emulsification Methods of Inline Mixing System RTES Produced by The Static Mixer and Ultrasonic on Fuel Consumption and Emission Characteristics," *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, vol. 78, no. 1, pp. 88–99, Dec. 2020, doi: 10.37934/arfmts.78.1.8899.
- [19] M. A. Ahmad *et al.*, "Combustion performance and exhaust emissions fuelled with non-surfactant water-in-diesel emulsion fuel made from different water sources," *Environmental Science and Pollution Research*, vol. 25, no. 24, pp. 24266–24280, Aug. 2018, doi: 10.1007/s11356-018-2492-2.
- [20] A. M. Ithnin *et al.*, "Emulsifier-free Water-in-Diesel emulsion fuel: Its stability behavior, engine performance and exhaust emission," *Fuel*, vol. 215, pp. 454–462, Mar. 2018, doi: 10.1016/j.fuel.2017.11.061.
- [21] D. A. Sugeng, A. M. Ithnin, W. J. Yahya, and H. Abd Kadir, "Emulsifier-Free Water-in-Biodiesel Emulsion Fuel via Steam Emulsification: Its Physical Properties, Combustion Performance, and Exhaust Emission," *Energies*, vol. 13, no. 20, p. 5406, Oct. 2020, doi: 10.3390/en13205406.
- [22] R. T. Omi *et al.*, "Performance and Emissions of Diesel Engine with Circulation Non-Surfactant Emulsion Fuel System," *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, vol. 82, no. 2, pp. 96–105, May 2021, doi: 10.37934/arfmts.82.2.96105.
- [23] W. N. I. W. Mahdi *et al.*, "The effect of different in-line mixers producing emulsifier-free bio-diesel emulsion on the diesel engine combustion performance and exhaust emission," *Fuel*, vol. 337, p. 126886, Apr. 2023, doi: 10.1016/j.fuel.2022.126886.
- [24] M. Q. Mohd Tamam *et al.*, "Performance and emission studies of a common rail turbocharged diesel electric generator fueled with emulsifier free water/diesel emulsion," *Energy*, vol. 268, p. 126704, Apr. 2023, doi: 10.1016/j.energy.2023.126704.
- [25] H. Wu, F. Xie, and Y. Han, "Effect of cetane coupled with various engine conditions on diesel engine combustion and emission," *Fuel*, vol. 322, p. 124164, Aug. 2022, doi: 10.1016/j.fuel.2022.124164.
- [26] R. Kizza, N. Banadda, and J. Seay, "Qualitative and energy recovery potential analysis: plastic-derived fuel oil versus conventional diesel oil," *Clean Technologies and Environmental Policy*, vol. 24, no. 3, pp. 789–800, Apr. 2022, doi: 10.1007/s10098-021-02028-9.
- [27] F. Faisal, M. G. Rasul, M. I. Jahirul, and A. A. Chowdhury, "Waste plastics pyrolytic oil is a source of diesel fuel: A recent review on diesel engine performance, emissions, and combustion characteristics," *Science of The Total Environment*, vol. 886, p. 163756, Aug.

- 2023, doi: 10.1016/j.scitotenv.2023.163756.
- [28] M. Sekar, T. R. Praveenkumar, V. Dhinakaran, P. Gunasekar, and A. Pugazhendhi, "Combustion and emission characteristics of diesel engine fueled with nanocatalyst and pyrolysis oil produced from the solid plastic waste using screw reactor," *Journal of Cleaner Production*, vol. 318, p. 128551, 2021, doi: 10.1016/j.jclepro.2021.128551.
- [29] F. Faisal, M. G. Rasul, A. A. Chowdhury, M. I. Jahirul, and M. A. Hazrat, "Performance and emission characteristics of a CI engine with post-treated plastic pyrolysis oil and diesel blend," *Energy Reports*, vol. 9, pp. 87–92, Nov. 2023, doi: 10.1016/j.egyr.2023.09.142.
- [30] A. G. M. B. Mustayen, M. G. Rasul, X. Wang, M. A. Hazrat, M. Negnevitsky, and M. I. Jahirul, "Impact of waste-plastic-derived diesel on the performance and emission characteristics of a diesel engine under low load conditions," *Energy Conversion and Management*, vol. 283, p. 116936, May 2023, doi: 10.1016/j.enconman.2023.116936.
- [31] C. P. Onuoha, I. N. Etim, and E. E. Oguzie, "Impact of water-in-diesel emulsion on compression ignition engine's emissions and its challenges—A detailed review," *Vietnam Journal of Chemistry*, vol. 62, no. 4, pp. 421–436, Aug. 2024, doi: 10.1002/vjch.202300368.
- [32] M. Q. Mohd Tamam *et al.*, "Engine performance and emissions evaluation of surfactant-free B30 biodiesel–diesel/water emulsion as alternative fuel," *Scientific Reports*, vol. 13, no. 1, p. 10599, Jun. 2023, doi: 10.1038/s41598-023-37662-4.
- [33] P. K. Mondal and B. K. Mandal, "A comprehensive review on the feasibility of using water emulsified diesel as a CI engine fuel," *Fuel*, vol. 237, pp. 937–960, Feb. 2019, doi: 10.1016/j.fuel.2018.10.076.
- [34] A. Wiangkham, N. Klinkaew, P. Aengchuan, P. Liplap, A. Ariyarat, and E. Sukjit, "Experimental and optimization study on the effects of diethyl ether addition to waste plastic oil on diesel engine characteristics," *RSC Advances*, vol. 13, no. 36, pp. 25464–25482, 2023, doi: 10.1039/D3RA04489K.
- [35] D. Saha and B. Roy, "Influence of areca nut husk nano-additive on combustion, performance, and emission characteristics of compression ignition engine fuelled with plastic-grocery-bag derived oil-water-diesel emulsion," *Energy*, vol. 268, p. 126682, Apr. 2023, doi: 10.1016/j.energy.2023.126682.
- [36] B. K. Debnath, U. K. Saha, and N. Sahoo, "A comprehensive review on the application of emulsions as an alternative fuel for diesel engines," *Renewable and Sustainable Energy Reviews*, vol. 42, pp. 196–211, Feb. 2015, doi: 10.1016/j.rser.2014.10.023.
- [37] M. D. Anil, V. B. Hemadri, and M. Swamy, "Experimental investigation on impact of water in diesel emulsion in a single-cylinder research diesel engine," *International Journal of Ambient Energy*, vol. 44, no. 1, pp. 399–412, Dec. 2023, doi: 10.1080/01430750.2022.2128411.
- [38] Y. M. Oo, J. Thawornprasert, N. Intaprom, K. Rodniem, and K. Somnuk, "Diesel–Biodiesel–Water Fuel Nanoemulsions for Direct Injection and Indirect Injection Diesel Engines: Performance and Emission Characteristics," *ACS Omega*, vol. 7, no. 39, pp. 34951–34965, Oct. 2022, doi: 10.1021/acsomega.2c03553.
- [39] A. Ali, A. R. A. Aziz, M. A. Ismael, and S. Alqaed, "Biosurfactants as an alternative eco-friendly solution for water-in-diesel emulsions-A review paper," *Heliyon*, vol. 10, no. 17, p. e37485, Sep. 2024, doi: 10.1016/j.heliyon.2024.e37485.
- [40] S. Vellaiyan and K. S. Amirthagadeswaran, "The role of water-in-diesel emulsion and its additives on diesel engine performance and emission levels: A retrospective review," *Alexandria Engineering Journal*, vol. 55, no. 3, pp. 2463–2472, Sep. 2016, doi: 10.1016/j.aej.2016.07.021.
- [41] V. L. Mangesh, S. Padmanabhan, P. Tamizhdurai, and A. Ramesh, "Experimental investigation to identify the type of waste plastic pyrolysis oil suitable for conversion to diesel engine fuel," *Journal of Cleaner Production*, vol. 246, p. 119066, 2020, doi: 10.1016/j.jclepro.2019.119066.
- [42] G. Soundararajan, B. Chidambaranathan, A. K. Rajendran, D. Venugopal, and Y. Devarajan, "Plastic pyrolytic oils as renewable fuel: improving its physical

- properties and ignition patterns by waste renewable source—an experimental analysis,” *Environmental Science and Pollution Research*, vol. 31, no. 18, pp. 26497–26509, Mar. 2024, doi: 10.1007/s11356-024-32668-5.
- [43] Z. Yang *et al.*, “Characterization of renewable diesel, petroleum diesel and renewable diesel/biodiesel/petroleum diesel blends,” *Renewable Energy*, vol. 224, p. 120151, Apr. 2024, doi: 10.1016/j.renene.2024.120151.
- [44] D. S. Devi, R. Kumar, and U. Rajak, “Experimental investigation of performance, emission and combustion characteristics of a CI engine fuelled by blends of waste plastic oil with diesel,” *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 44, no. 3, pp. 7693–7708, Sep. 2022, doi: 10.1080/15567036.2022.2115582.
- [45] N. Karisathan Sundararajan and A. R. B. Ammal, “Improvement studies on emission and combustion characteristics of DIC engine fuelled with colloidal emulsion of diesel distillate of plastic oil, TiO₂ nanoparticles and water,” *Environmental Science and Pollution Research*, vol. 25, no. 12, pp. 11595–11613, Apr. 2018, doi: 10.1007/s11356-018-1380-0.
- [46] F. R. Saputro *et al.*, “Effects of oxyhydrogen enrichment on diesel engine performance and emissions using B35 and its water-in-biodiesel emulsion,” *International Journal of Hydrogen Energy*, vol. 142, pp. 109–121, Jun. 2025, doi: 10.1016/j.ijhydene.2025.05.359.
- [47] J. Park and J. Oh, “Study on the characteristics of performance, combustion, and emissions for a diesel water emulsion fuel on a combustion visualization engine and a commercial diesel engine,” *Fuel*, vol. 311, p. 122520, Mar. 2022, doi: 10.1016/j.fuel.2021.122520.
- [48] C. Liu *et al.*, “A model for evaluating the micro-explosion of a single droplet of water-in-oil emulsions and the effect of hydrophilic surfactants on the phenomenon,” *Chemical Engineering Science*, vol. 262, p. 118047, Nov. 2022, doi: 10.1016/j.ces.2022.118047.
- [49] S. Ren, Z. Wang, B. Li, H. Liu, and J. Wang, “Development of a reduced polyoxymethylene dimethyl ethers (PODE_n) mechanism for engine applications,” *Fuel*, vol. 238, pp. 208–224, Feb. 2019, doi: 10.1016/j.fuel.2018.10.111.
- [50] N. Kumar, H. S. Pali, and S. Bansal, “Some Studies on NO_x Reduction From a Diesel Engine Using Stabilized Emulsion,” in *ASME 2018 International Mechanical Engineering Congress and Exposition*, American Society of Mechanical Engineers, Nov. 2018. doi: 10.1115/IMECE2018-87374.
- [51] H. Yang, S. R. Krishnan, K. K. Srinivasan, and K. C. Midkiff, “Modeling of NO_x Emissions Using a Super-Extended Zel’dovich Mechanism,” in *Design and Control of Diesel and Natural Gas Engines for Industrial and Rail Transportation Applications*, ASMEDC, Jan. 2003, pp. 121–128. doi: 10.1115/ICEF2003-0713.
- [52] M. Q. M. Tamam *et al.*, “Application of an Inline Mixer to Produce Surfactant-Free Biodiesel-diesel/Water Emulsion Fuel: An Analysis of Water Droplets Characteristics and Drive Cycle Emissions,” *Arabian Journal for Science and Engineering*, vol. 50, no. 12, pp. 9261–9274, Jun. 2025, doi: 10.1007/s13369-024-09408-5.
- [53] I. Kalargaris, G. Tian, and S. Gu, “Experimental evaluation of a diesel engine fuelled by pyrolysis oils produced from low-density polyethylene and ethylene–vinyl acetate plastics,” *Fuel Processing Technology*, vol. 161, pp. 125–131, Jun. 2017, doi: 10.1016/j.fuproc.2017.03.014.
- [54] Y. Yan, T. Shang, L. Li, R. Yang, Z. Liu, and J. Liu, “Numerical Investigation of In-Cylinder Combustion Behaviors in a Medium-Speed Diesel Engine,” *Journal of Energy Resources Technology*, vol. 146, no. 8, Aug. 2024, doi: 10.1115/1.4065289.
- [55] A. N. Dibofori-Orji, “Critical processes involved in formulation of water-in-oil fuel emulsions, combustion efficiency of the emulsified fuels and their possible environmental impacts,” *Research Journal of Applied Sciences, Engineering and Technology*, vol. 3, no. 8, pp. 701–706, 2011.
- [56] K. Kusmiyati and A. Fudholi, “A systematic literature review on the pyrolysis of plastic waste and waste oil for fuel production: Targeted waste management solution for central Java, Indonesia,” *Cleaner Waste*

- Systems*, vol. 11, p. 100308, Jun. 2025, doi: 10.1016/j.clwas.2025.100308.
- [57] G. A. Bin Mukhtar, T. Nagata, J. Hayashi, N. Horibe, H. Kawanabe, and M. Fuchihata, "Analysis of emission and combustion behaviors of water-emulsified diesel with various water contents and droplet diameters," *Journal of Thermal Science and Technology*, vol. 20, no. 1, pp. 24–00385, 2025, doi: 10.1299/jtst.24-00385.
- [58] H. Watanabe, Y. Suzuki, T. Harada, Y. Matsushita, H. Aoki, and T. Miura, "An experimental investigation of the breakup characteristics of secondary atomization of emulsified fuel droplet," *Energy*, vol. 35, no. 2, pp. 806–813, Feb. 2010, doi: 10.1016/j.energy.2009.08.021.
- [59] Y. Han, Z. Tian, J. Xu, Q. Liang, Z. Dai, and F. Wang, "A new experimental method for studying the single droplet breakup mode of diesel-water composite droplet fuel," *Petroleum Science and Technology*, vol. 43, no. 12, pp. 1275–1292, Jun. 2025, doi: 10.1080/10916466.2024.2325602.
- [60] M. Yahaya Khan, Z. A. Abdul Karim, F. Y. Hagos, A. R. A. Aziz, and I. M. Tan, "Current Trends in Water-in-Diesel Emulsion as a Fuel," *The Scientific World Journal*, vol. 2014, pp. 1–15, 2014, doi: 10.1155/2014/527472.
- [61] P. S. Kumar and G. Sankaranarayanan, "Investigation on environmental factors of waste plastics into oil and its emulsion to control the emission in DI diesel engine," *Ecotoxicology and Environmental Safety*, vol. 134, pp. 440–444, Dec. 2016, doi: 10.1016/j.ecoenv.2016.01.021.
- [62] N. C. Belay, B. A. Fentaw, R. B. Nallamotheu, and M. S. Kebede, "Performance evaluation of liquid fuel derived from waste plastics for diesel engine applications and emissions characteristics," *Energy*, vol. 318, p. 134911, Mar. 2025, doi: 10.1016/j.energy.2025.134911.
- [63] P. B. Senthilkumar, M. Parthasarathy, R. Nagarajan, N. Murgunachiappan, P. V. Elumalai, and B. H. Varaprasad, "The effect of thermal degradation and thermogravimetric analysis on pyrolysis oil production from waste milk packet for CI engine application," *Journal of Thermal Analysis and Calorimetry*, vol. 147, no. 17, pp. 9677–9691, Sep. 2022, doi: 10.1007/s10973-022-11226-6.