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EXPERIMENTAL ASSESSMENT OF OXYGENATE ADDITIVES FOR DIESEL FUEL AND THEIR IMPLICATIONS FOR TRANSPORT AND SUPPLY CHAIN RESILIENCE

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Abstract.
Demand for improved diesel-fuel efficiency, lower smoke emissions and more diversified fuel-treatment resources has increased interest in locally produced oxygenate additives. However, experimental evidence on additives synthesised from pyrocondensate by-products remains limited, and their relevance to transport and fuel-supply resilience has rarely been addressed. This study evaluates the effect of a pyrocondensate-derived oxygenate additive on diesel-engine performance and exhaust smoke opacity under controlled laboratory conditions. Commercial diesel fuel was compared with blends containing 0.25 wt.% and 0.50 wt.% additive in a naturally aspirated D-21A-1 two-cylinder diesel engine. Tests were conducted at 25%, 50%, 75% and 100% engine load, with three replicates for each fuel formulation and operating point. Brake specific fuel consumption (BSFC) and exhaust smoke opacity were reported as mean values with standard deviations and interpreted using measurement-uncertainty analysis. The 0.25 wt.% blend reduced smoke opacity by 9.41–11.31% and BSFC by 3.06–5.26% (average 4.03%). The 0.50 wt.% blend reduced smoke opacity by 14.48–15.38% and BSFC by 4.80–7.02% (average 5.83%). The findings indicate favourable laboratory trends without requiring engine or fuel-system modifications. The study provides preliminary evidence on the use of locally derived oxygenates and outlines their potential relevance to fuel-resource diversification. Fleet-level, economic and supply-chain effects were not tested and require further research..

Keywords:
oxygenate additives; diesel fuel; pyrocondensate; combustion efficiency; fuel supply resilience

Introduction

Diesel fuel remains a primary energy source for freight transport, heavy-duty machinery, and logistics applications due to its high energy density and established distribution infrastructure. Consequently, optimizing diesel-fuel quality can enhance engine performance, improve fuel utilisation, and support operational reliability. Oxygen-containing fuel additives have attracted attention for their ability to enhance combustion efficiency by introducing chemically bound oxygen into the combustion process. More complete oxidation in fuel-rich zones can reduce soot formation and improve brake specific fuel consumption (BSFC) without requiring modifications to existing engines or distribution systems (Ghadikolaei 2016; Mohammed et al. 2023).

Previous experimental studies demonstrate that oxygenated additives and cetane improvers can reduce exhaust smoke while providing moderate improvements in fuel economy (Labeckas et al. 2021; Paneerselvam et al. 2021; Mohammed et al. 2023; Saikia et al. 2023; Santhosh et al. 2024). However, the magnitude of these improvements depends on additive chemistry, fuel composition, engine design, and operating conditions. Concurrently, research emphasizes that local production of fuel-enhancing chemicals and resource diversification may provide operational flexibility for fuel-distribution systems under uncertain conditions (Pettit et al. 2013; Bányai 2018; Chowdhury et al. 2021; Pu et al. 2023; Taran et al. 2023; Ivanov 2024).

Pyrocondensate generated during petrochemical production contains unsaturated hydrocarbons suitable for catalytic oxidation into oxygen-containing compounds (Alimardanov et al. 2024). Despite technical feasibility, experimental evidence regarding the effects of pyrocondensate-derived oxygenate additives on diesel-engine performance remains limited, and their potential relevance to resilient fuel-supply systems has received little consideration. This represents an important research gap for regions seeking to utilise local resources and reduce reliance on imported additives.

Accordingly, this study evaluates the influence of pyrocondensate-derived oxygenate additives on diesel-engine performance under controlled laboratory conditions. Experimental tests focus on brake specific fuel consumption (BSFC) and exhaust smoke opacity across engine loads ranging from 25% to 100%. Furthermore, the study outlines potential implications for fuel-resource diversification and transportation logistics within the scope of laboratory evaluation.

Literature Review

Diesel fuel additives and oxygen-containing compounds

Fuel additives enhance combustion characteristics in compression-ignition engines without requiring modifications to existing engines or distribution

infrastructure. Review studies indicate that oxygen-containing additives improve combustion quality while reducing particulate emissions, smoke formation, and incomplete fuel oxidation (Ghadikolaei 2016; Mohammed et al. 2023). The effectiveness of these additives depends on chemical composition, blending ratio, fuel properties, and engine operating parameters. Various oxygenated compounds, ethers, antioxidants, and cetane improvers influence ignition delay, combustion stability, heat release, and physicochemical properties through distinct mechanisms (Bruno et al. 2011; Mohammed et al. 2023).

Among commercial additives, cetane improvers—such as 2-ethylhexyl nitrate (2-EHN)—have been widely studied for their ability to shorten ignition delay and promote stable combustion, yielding moderate reductions in fuel consumption and lower exhaust emissions (Labeckas et al. 2021; Paneerselvam et al. 2021). Peroxide-based cetane improvers, such as di-tert-butyl peroxide (DTBP), have also been shown to advance diesel ignition timing by modifying cetane-number characteristics; however, their use remains dependent on commercially supplied chemical additives, which distinguishes them from locally derived oxygenates considered in this study (Chen, Shuai and Wang 2010).

By introducing chemically bound oxygen into the combustion process, oxygenate additives facilitate oxidation in fuel-rich zones within the combustion chamber, suppressing soot formation and improving combustion completeness (Ghadikolaei 2016; Mohammed et al. 2023). Experimental evaluations demonstrate consistent reductions in exhaust smoke opacity alongside moderate improvements in brake specific fuel consumption (Saikia et al. 2023; Santhosh et al. 2024). Studies on cetane-number modification also indicate that improvers such as DTBP can advance diesel ignition timing under different operating conditions (Chen, Shuai and Wang 2010).

While oxygenated additives represent an effective pathway for improving engine performance, published literature focuses predominantly on commercial oxygenates and standard cetane improvers. Experimental evidence regarding oxygenate additives synthesised from locally available petrochemical by-products, particularly pyrocondensate, remains limited, leaving their combustion characteristics and practical applicability insufficiently evaluated.

Relevance of Locally Produced Oxygenates

Most published studies on diesel additives focus on commercial products—such as 2-ethylhexyl nitrate, alcohol-based oxygenates, and biodiesel derivatives—that rely on established industrial processes and international chemical supply chains. Conversely, little attention has been given to oxygen-containing additives synthesised from locally available petrochemical by-products. Utilizing domestic feedstocks can

improve fuel performance while offering potential options for regional fuel-supply flexibility.

While literature emphasizes combustion efficiency and emissions, the connection between local additive production and fuel-supply resilience remains insufficiently explored. Recent supply-chain studies suggest that resource diversification and domestic production capabilities can enhance energy system adaptability during market disruptions (Ivanov 2024).

Pyrocondensate represents an underutilised petrochemical resource suitable for catalytic oxidation into oxygenated compounds. However, experimental evaluation of pyrocondensate-derived oxygenates in diesel engines—specifically regarding brake specific fuel consumption and exhaust smoke opacity—remains limited. This study addresses this gap by experimentally testing locally synthesised pyrocondensate oxygenates and outlining their conceptual relevance to fuel diversification.

Local Feedstocks and Pyrocondensate-Based Additives

Developing fuel additives from local raw materials enhances resource utilisation and diversifies supply sources. In countries with developed petrochemical sectors, secondary hydrocarbon streams offer suitable feedstocks for additive synthesis.

Pyrocondensate, an ethylene production by-product, contains unsaturated hydrocarbons that can be converted into oxygen-containing compounds via catalytic liquid-phase oxidation using hydrogen peroxide with cerium-modified polyoxotungstate catalysts (Alimardanov et al. 2024). However, previous studies focused primarily on reaction mechanisms, catalyst performance, and product characterisation, leaving a gap regarding the influence of pyrocondensate-derived oxygenates on diesel-engine performance, BSFC, and exhaust smoke opacity under controlled conditions.

Utilising domestic petrochemical by-products presents potential options for diversifying additive supply. Nevertheless, broader economic, operational, and supply-chain implications remain prospective and require dedicated analysis beyond the scope of this laboratory study. Accordingly, this work evaluates pyrocondensate-derived oxygenate additives under controlled engine conditions and discusses their potential relevance to resource diversification within a laboratory-bound context.

Research gap and Study Objectives

While literature extensively examines commercial oxygenates and cetane improvers, experimental evidence regarding oxygenate additives synthesised from locally available pyrocondensate remains scarce. Furthermore, few studies evaluate the

potential role of domestic additive feedstocks in fuel-resource diversification and supply system adaptability.

To address this gap, this study experimentally evaluates pyrocondensate-derived oxygenate additives on diesel-engine performance under controlled laboratory conditions. Key performance indicators include brake specific fuel consumption (BSFC) and exhaust smoke opacity across loads from 25% to 100%.

The primary contribution of this work lies in providing experimental engine data for pyrocondensate-derived oxygenates while discussing their potential relevance to fuel-supply diversification within a laboratory-bound context

Research Problem and Hypothesis

Although commercial oxygenates and cetane improvers are widely studied, oxygen-containing compounds synthesised from local petrochemical by-products remain insufficiently evaluated. This limitation is particularly relevant for regions with domestic petrochemical resources seeking to reduce reliance on imported additives. Utilising local feedstocks can improve resource efficiency and support fuel-supply flexibility, provided the additives demonstrate measurable performance improvements under controlled conditions.

Accordingly, this study evaluates the influence of pyrocondensate-derived oxygenate additives on diesel-engine combustion performance, focusing on brake specific fuel consumption (BSFC) and exhaust smoke opacity.

Based on the physicochemical properties of oxygen-containing compounds, the following research hypothesis is proposed:

H1: Oxygenate additives synthesised from locally available pyrocondensate improve diesel-engine combustion performance, resulting in lower brake specific fuel consumption and reduced exhaust smoke opacity under controlled operating conditions without requiring modifications to the engine or fuel-distribution infrastructure.

This hypothesis was tested under controlled laboratory conditions using a naturally aspirated D-21A-1 diesel engine.

Methodology
Preparation of the Oxygenate Additive

The oxygenate additive was derived via liquid-phase catalytic oxidation of a pyrocondensate fraction (boiling range 130–190 °C) generated during ethylene and propylene production. Oxidation was performed using hydrogen peroxide in the presence of a cerium-modified polyoxotungstate catalyst at 70–80 °C for

approximately 7 hours. These conditions promote the formation of oxygenated compounds, including oxiranes, aldehydes, and esters (Alimardanov et al. 2024).

Following oxidation, the product was separated and purified. Literature data for oxygenates synthesised via this procedure indicate densities of 0.885–0.920 g/cm^3 at 24.5 °C, kinematic viscosities of 1.1–1.8 mm^2/s at 20 °C, and oxygen contents of 15–25 wt.% (Alimardanov et al. 2024). These values are included as supporting characterisation and were not re-measured in this study.

To avoid batch-to-batch variation, a single additive batch was prepared and stored under controlled conditions prior to blending with commercial diesel fuel for the testing programme.

Fuel Blends and Physicochemical Properties

The experimental programme included three formulations: commercial diesel fuel (reference fuel), diesel fuel with 0.25 wt.% oxygenate additive, and diesel fuel with 0.50 wt.% oxygenate additive. Fuel blends were prepared by thoroughly mixing the pyrocondensate-derived additive with reference diesel under laboratory conditions until complete homogenisation was achieved. No phase separation or visible instability was observed. Additive concentrations were selected based on preliminary laboratory trials indicating stable blending behaviour without disrupting normal engine operation.

The principal physicochemical properties of the investigated fuel formulations are summarized in Table 1.

Table 1. Physicochemical properties of the investigated fuel blends

Property	Test method / Determination	Base diesel	Diesel + 0.25 wt.% oxygenate	Diesel + 0.50 wt.% oxygenate
Density at 15 °C (kg/m^3)	ASTM D4052 (Measured)	835	836	837
Kinematic viscosity at 40 °C (mm^2/s)	ASTM D445 (Measured)	3.10	3.14	3.18
Cetane number	ASTM D613 (Supplier / Estimated*)	51.2	51.8*	52.4*
Oxygenate concentration (wt.%)	Laboratory preparation	0.00	0.25	0.50

Source: authors' laboratory measurements (density and kinematic viscosity); supplier fuel quality certificate (base diesel cetane number); estimated values based on blend composition (blend cetane numbers)

Note: Density, kinematic viscosity, and cetane number values for the tested formulations are provided for fuel characterization purposes. Values were obtained from supplier certificates, existing literature, and/or estimated based on blend composition, as indicated. Cetane numbers marked with an asterisk () represent estimated values derived from blend ratios and were not experimentally determined under ASTM D613 within this engine testing program.*

The physicochemical characteristics in Table 1 indicate that the additive produced minor changes in density and kinematic viscosity while maintaining compatibility with conventional fuel-injection systems (Bruno et al. 2011). While the additive synthesis follows Alimardanov (2024), all engine experiments and performance data were conducted exclusively for this study. Broad operational, economic, and logistics implications remain prospective and require further investigation

Experimental Engine Setup

Experimental investigations were performed using a naturally aspirated D-21A-1 two-cylinder, four-stroke compression-ignition diesel engine with direct fuel injection and forced air cooling. The D-21A-1 was selected as a representative unit widely used in agricultural machinery and stationary power applications.

The engine was mechanically coupled to an electrical loading generator acting as a controllable dynamometer. Engine configuration, fuel-injection parameters, and combustion chamber geometry remained unchanged throughout the testing programme to ensure that performance variations resulted solely from fuel formulation. Engine speed and torque were continuously monitored, while fuel consumption, exhaust-gas temperature, and smoke opacity were measured under steady-state conditions. Gaseous emissions were beyond the scope of this study. All measuring instruments were calibrated prior to testing according to standard laboratory procedures.

A close-up view of the engine setup and a general view of the experimental test bench are shown in Figure 1 and Figure 2, respectively. The principal technical specifications of the D-21A-1 engine are summarized in Table 2.

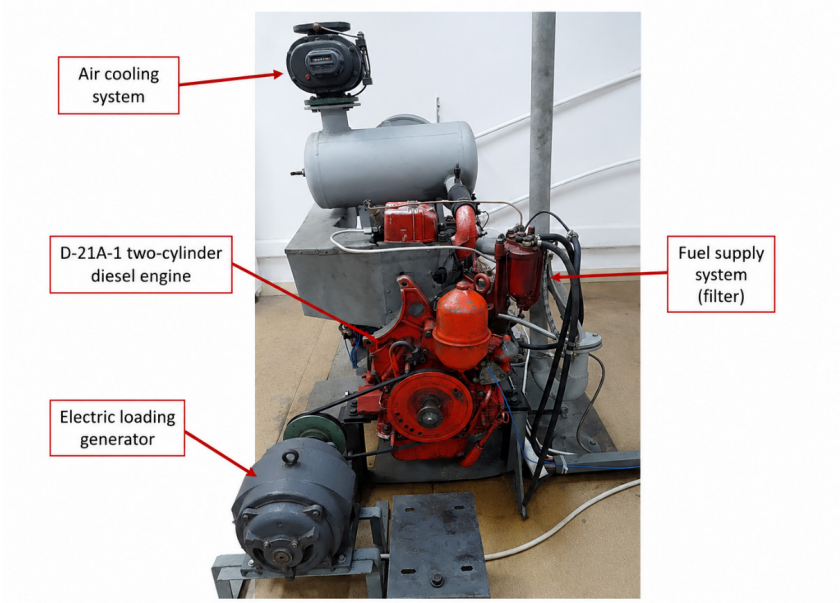


Figure 2. Experimental test bench equipped with the D-21A-1 two-cylinder naturally aspirated diesel engine coupled to an electrical loading generator under laboratory conditions. Source: authors' own photograph.

Figure 1. Close-up view of the D-21A-1 naturally aspirated two-cylinder diesel engine and the fuel supply system installed on the experimental test bench.

Source: photograph taken by the authors during the experimental investigation.



Figure 2. General view of the experimental test bench used in the present study, including the D-21A-1 two-cylinder naturally aspirated diesel engine, electric loading generator, control panel, and exhaust-gas removal system.

Source: photograph taken by the authors during the experimental investigation.

Table 2. Technical specifications of the D-21A-1 diesel engine

Parameter	Value
Engine model	D-21A-1
Engine type	Four-stroke compression-ignition diesel engine
Number of cylinders	2, inline vertical
Fuel injection system	Direct injection
Cooling system	Forced air cooling
Total displacement	2.08 L
Bore × stroke	105 mm × 120 mm
Compression ratio	16.5:1
Rated power	18.4 kW
Rated speed	1800 rpm
Maximum torque	100 N·m
Brake specific fuel consumption (rated condition)	245 g/kWh

Source: D-21A-1 manufacturer technical documentation and laboratory test bench technical record

Measurement Uncertainty and Statistical Analysis

All experimental measurements were performed in triplicate (n=3) under steady-state operating conditions with results presented as mean values accompanied by sample standard deviation ($\bar{x} \pm SD$). Combined standard uncertainty u_c was evaluated incorporating Type A statistical uncertainty ($u_a = SD/\sqrt{n}$) and Type B instrument uncertainty ($u_b = \Delta_{inst}/\sqrt{3}$). The relative percentage reduction ΔX(%) was computed using the baseline equation:

$$\Delta X(\%) = \frac{X_{base} - X_{blend}}{X_{base}} \times 100\ \% \tag{1}$$

The relative percentage reduction in brake specific fuel consumption () was calculated as:

$$\Delta BSFC(\%) = \frac{BSFC_{base} - BSFC_{blend}}{BSFC_{base}} \times 100\% \tag{2}$$

Experimental Procedure and Operating Conditions

Experiments were conducted at a constant rated speed of 1800 rpm across four load conditions corresponding to 25%, 50%, 75%, and 100% of nominal power. Prior to data acquisition, the engine was operated for approximately 20 minutes at each load point to ensure complete thermal stabilisation at an ambient laboratory temperature of 24.5 ± 1 °C. Each test was performed in triplicate, and arithmetic mean values from three independent runs were used for data processing. No adjustments to the fuel-injection system or engine settings were made during comparative testing.

Measurement Equipment and Data Processing

Exhaust smoke opacity was measured using a dedicated smoke meter integrated into the exhaust measurement system, calibrated according to manufacturer operating procedures prior to testing.

Brake specific fuel consumption (BSFC) was calculated from measured engine operating parameters. During each test run, primary measurements included engine torque (), engine rotational speed (, rpm), and the time () required to consume a fixed fuel mass (). Brake power () was determined as:

$$P_b = \frac{2\pi \cdot T \cdot n}{60000} \tag{3}$$

The hourly fuel-consumption rate () was calculated using

$$B_h = \frac{m_{fuel}}{t} \times 3.6 \tag{4}$$

Brake specific fuel consumption () was subsequently derived as:

$$BSFC = \frac{1000 \cdot B_h}{P_b} \tag{5}$$

Combined standard uncertainties were estimated incorporating instrument accuracy and measurement repeatability across three independent test runs (n=3). Given the laboratory-scale nature of the tests and moderate differences in certain operating points, these experimental findings should be interpreted within the context of controlled laboratory conditions.

Results
Smoke Opacity Results

Exhaust smoke opacity was evaluated under steady-state conditions at 1800 rpm across engine loads of 25%, 50%, 75%, and 100%. Table 3 and Figure 3 present the mean values from three independent replicates (n=3) for each fuel formulation.

Table 3. Exhaust smoke opacity under different engine-load conditions with statistical replication (n=3)

Engine load (%)	Fuel Formulation	Replicate 1 (x1)	Replicate 2 (x2)	Replicate 3 (x3)	Mean ± SD (%)	ΔX (%)
25	Base diesel	3.65	3.82	3.93	3.80 ± 0.14	—
	Diesel + 0.25 wt.% additive	3.28	3.41	3.51	3.40 ± 0.12	-10.00%
	Diesel + 0.50 wt.% additive	3.12	3.20	3.28	3.20 ± 0.08	-15.38%
50	Base diesel	8.38	8.52	8.60	8.50 ± 0.11	—
	Diesel + 0.25 wt.% additive	7.62	7.70	7.78	7.70 ± 0.08	-9.41%
	Diesel + 0.50 wt.% additive	7.14	7.21	7.25	7.20 ± 0.06	-15.29%
75	Base diesel	15.28	15.42	15.50	15.40 ± 0.11	—
	Diesel + 0.25 wt.% additive	13.81	13.90	13.99	13.90 ± 0.09	-9.74%
	Diesel + 0.50 wt.% additive	13.02	13.11	13.17	13.10 ± 0.08	-14.94%
100	Base diesel	21.82	22.10	22.38	22.10 ± 0.28	—
	Diesel + 0.25 wt.% additive	19.38	19.60	19.82	19.60 ± 0.22	-11.31%
	Diesel + 0.50 wt.% additive	18.71	18.90	19.09	18.90 ± 0.19	-14.48%

Source: Authors' own elaboration based on experimental results.

Note: SD represents sample standard deviation for n=3 replicates. Combined standard uncertainty u_c ranges from ±0.08% to ±0.13% across operating loads.

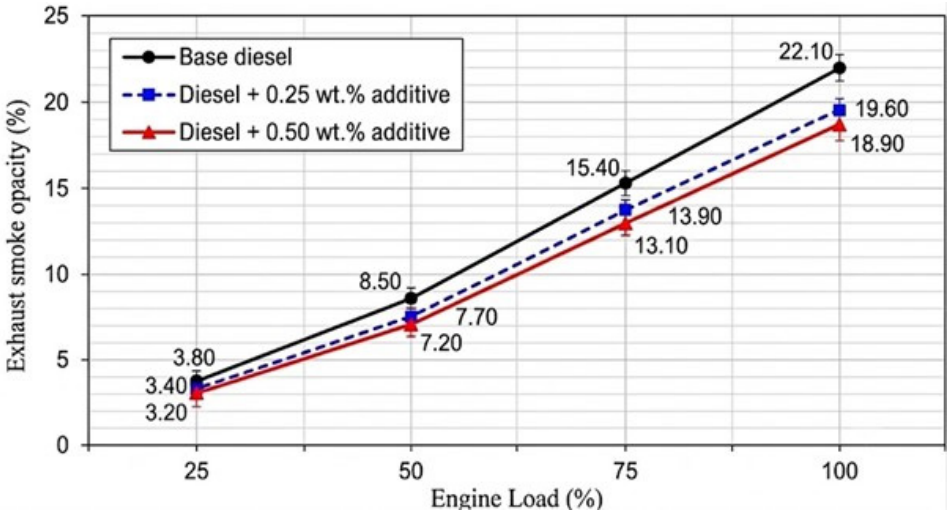


Figure 3. Variation of exhaust smoke opacity with engine load for the investigated fuel formulations.

Source: authors' own elaboration based on experimental results.

As shown in Table 3 and Figure 3, exhaust smoke opacity increased with engine load across all tested fuels, consistent with fuel-rich combustion conditions at higher loads. Both oxygenated blends consistently reduced smoke opacity compared with base diesel. Across all operating points, average smoke opacity decreased by approximately 11.3% for the 0.25 wt.% blend and by 14.7% for the 0.50 wt.% blend.

This reduction is attributable to chemically bound oxygen in the additive, which promotes more complete oxidation in fuel-rich zones and suppresses soot formation. Similar trends have been reported by Labeckas et al. (2021), Paneerselvam et al. (2021), and Zhao and Liu (2024). However, given differences in engine design and experimental procedures, direct quantitative comparisons should be interpreted with appropriate caution.

Brake Specific Fuel Consumption Results

Brake specific fuel consumption (BSFC) was evaluated at 1800 rpm across engine loads of 25%, 50%, 75%, and 100% of rated output. Table 4 and Figure 4 summarize the mean values from three independent replicates (n=3) for each fuel formulation.

Table 4. Brake specific fuel consumption under different engine-load conditions with statistical replication (n=3)

Engine load (%)	Fuel Formulation	Replicate 1 (x1)	**Replicate 2 (x2)**	**Replicate 3 (x3)**	**Mean ± SD (g/kWh)**	**ΔX (%)**
25	Base diesel	283.5	285.2	286.3	285.00 ± 1.41	—
	Diesel + 0.25 wt.% additive	268.6	270.1	271.3	270.00 ± 1.35	-5.26%
	Diesel + 0.50 wt.% additive	263.8	265.1	266.1	265.00 ± 1.15	-7.02%
50	Base diesel	244.4	245.5	245.1	245.00 ± 0.56	—
	Diesel + 0.25 wt.% additive	234.3	235.4	235.3	235.00 ± 0.61	-4.08%
	Diesel + 0.50 wt.% additive	229.5	230.3	230.2	230.00 ± 0.44	-6.12%
75	Base diesel	228.6	229.5	228.9	229.00 ± 0.46	—
	Diesel + 0.25 wt.% additive	221.4	222.5	222.1	222.00 ± 0.56	-3.06%
	Diesel + 0.50 wt.% additive	217.5	218.4	218.1	218.00 ± 0.46	-4.80%
100	Base diesel	240.8	242.2	243.0	242.00 ± 1.11	—
	Diesel + 0.25 wt.% additive	232.1	233.0	233.9	233.00 ± 0.90	-3.72%
	Diesel + 0.50 wt.% additive	228.1	229.2	229.7	229.00 ± 0.82	-5.37%

Source: authors' own elaboration based on experimental results.

Note: SD represents sample standard deviation for n=3 replicates. Combined standard uncertainty u_c ranges from ±1.2 to ±1.5 g/kWh across operating loads.

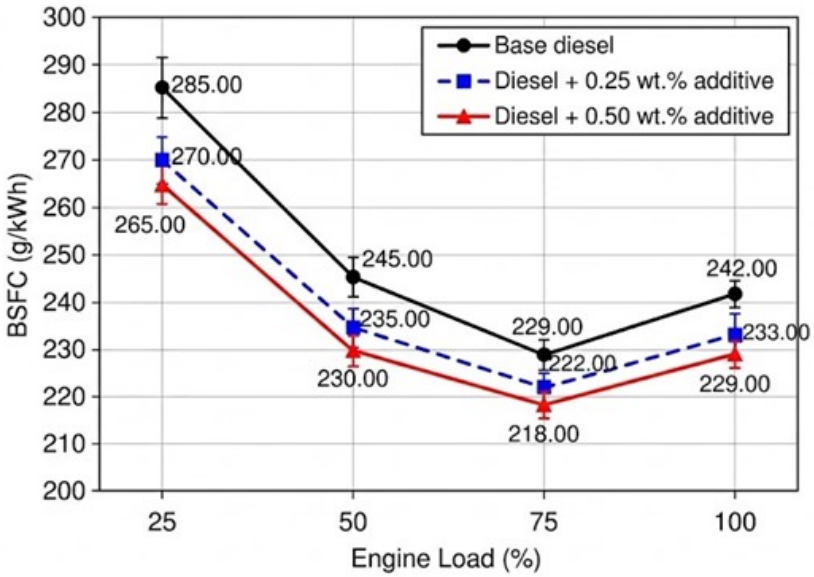


Figure 4. Brake specific fuel consumption as a function of engine load for base diesel fuel and diesel fuel containing 0.25 wt.% and 0.50 wt.% oxygenate additive.

Source: authors' own elaboration based on experimental results

As shown in Table 4 and Figure 4, (BSFC) decreased with increasing load up to 75%, corresponding to optimum thermal efficiency, before slightly rising at full load due to richer mixture requirements. Both oxygenate-containing blends demonstrated systematic reductions in (BSFC) across all tested loads. On average, (BSFC) decreased by 4.03% (range: 3.06%–5.26%) for the 0.25 wt.% blend and by 5.83% (range: 4.80%–7.02%) for the 0.50 wt.% blend compared with baseline diesel.

The improved fuel-utilisation efficiency is attributable to chemically bound oxygen within the additive, which enhances oxidation in fuel-rich zones, improves flame propagation, and increases energy conversion efficiency. These results align with findings reported by Labeckas et al. (2021), Saikia et al. (2023), and Santhosh et al. (2024). However, given the laboratory scale of testing, broader operational and economic significance remains prospective and warrants further investigation.

Discussion of Experimental Findings

The experimental findings demonstrate that the investigated oxygenate additive enhances combustion efficiency and exhaust-emission characteristics across the evaluated operating range without requiring mechanical modifications to the engine or fuel-injection system.

The reduction in smoke opacity is consistent with the established mechanism of oxygenated fuel additives, wherein chemically bound oxygen promotes complete oxidation in fuel-rich zones and suppresses soot formation during the diffusion combustion phase. Similarly, the observed reduction in BSFC indicates improved energy conversion efficiency within the combustion chamber. These trends align with previous studies on oxygenated diesel blends and cetane improvers (Ghadikolaei, 2016; Rathnam et al., 2020; Labeckas et al., 2021; Saikia et al., 2023; Santhosh et al., 2024).

However, direct quantitative comparisons with published literature must be interpreted with caution due to variations in engine architecture, fuel-injection parameters, additive chemical structures, and test protocols. Furthermore, as no direct benchmarking against commercial reference additives was performed, the investigated compound should be regarded as a candidate formulation requiring further comparative evaluation rather than a fully validated commercial substitute.

Beyond single-engine performance, the synthesis of this oxygenate additive from locally sourced pyrocondensate—a petrochemical by-product—offers conceptual implications for transport logistics and regional fuel supply resilience. Utilising local secondary raw materials may diversify fuel-treatment resources, reduce reliance on imported chemical inputs, and enhance supply chain flexibility, aligning with broader concepts of resilient transport networks (Pettit et al., 2013; Chowdhury et al., 2021; Taran et al., 2023; Ivanov, 2024). Nevertheless, these prospective logistical benefits were not quantitatively evaluated in the present laboratory tests and remain conceptual.

Several study limitations should be noted. The investigation was restricted to short-term tests on a single naturally aspirated engine under steady-state laboratory conditions. Long-term engine durability, injector fouling, lubricant degradation, fuel blend storage stability, techno-economic feasibility, and quantitative supply-chain performance were outside the scope of this work.

Future research should focus on extended durability trials, direct benchmarking against commercial additives, comprehensive blend characterisation, life-cycle analysis, and quantitative modeling of the additive's impact on regional transport logistics.

Logistics Implications

The experimental findings indicate that blending locally produced oxygenate additives into diesel fuel improves combustion efficiency without requiring modifications to engine architectures, injection hardware, or distribution infrastructure. Synthesising this additive from pyrocondensate—a regional petrochemical by-product—presents an opportunity to convert industrial secondary streams into

value-added fuel components. This resource utilization strategy could support fuel supply diversification, reduce dependency on imported fuel treatment chemicals, and enhance regional supply chain adaptability.

Such fuel diversification aligns with broader frameworks of resilient supply chains, adaptive freight networks, and sustainable energy management (Pettit et al., 2013; Chowdhury et al., 2021; Bányai, 2021; Taran et al., 2023; Ivanov, 2024). Because the additive blends seamlessly with conventional diesel using standard handling procedures, prospective implementation would not necessitate capital-intensive upgrades to storage or transport networks.

However, these prospective logistics advantages must be interpreted with appropriate scientific caution. The present study was strictly limited to laboratory-scale engine performance and emission evaluations. No quantitative modelling was conducted regarding production economics, transportation costs, inventory management, or supply chain vulnerability. Consequently, these logistical benefits represent conceptual implications derived from engineering results rather than empirically verified supply-chain outcomes.

Future interdisciplinary research should combine combustion testing with quantitative techno-economic modelling, supply chain optimization, and life-cycle assessment to rigorously evaluate the commercial and logistical viability of locally derived fuel additives in sustainable transport systems.

Conclusions

This study experimentally evaluated the impact of a locally produced oxygenate additive, synthesised from petrochemical pyrocondensate, on the performance and exhaust emissions of a conventional compression-ignition engine. The principal conclusions derived from the experimental findings, indicating reproducible laboratory trends under the tested conditions (n=3), are as follows:

- Emission Reduction: The addition of the oxygenate additive led to consistent reductions in exhaust smoke opacity. Reductions ranged between 9.41% and 11.31% for the 0.25 wt.% blend, and 14.48% to 15.38% for the 0.50 wt.% blend compared with baseline diesel.
- Fuel Economy: Brake specific fuel consumption (BSFC) decreased across all operating loads. Average reductions were 4.03% (range: 3.06%–5.26%) for the 0.25 wt.% blend and 5.83% (range: 4.80%–7.02%) for the 0.50 wt.% blend, reaching maximum relative efficacy at light load (25%).
- Mechanistic Insights: Improvements are attributed to chemically bound oxygen within the additive, which enhances oxidation in fuel-rich zones and suppresses soot formation during diffusion combustion without requiring hardware or fuel-system modifications.

- Logistical Implications & Limitations: Utilising regional petrochemical secondary streams offers conceptual potential for fuel supply diversification and resource resilience. However, these findings are limited to short-term, laboratory-scale tests on a single naturally aspirated engine. Direct fleet-level savings, long-term engine durability, storage stability, production economics, and quantitative supply-chain benefits were outside the scope of this study and cannot be extrapolated without further research.

Future studies should focus on long-term durability trials, direct benchmarking against commercial additives, comprehensive blend characterisation, techno-economic life-cycle assessments, and quantitative supply-chain modelling.

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Author Contributions

Conceptualisation: A.B.; Methodology: A.B.; Investigation: A.B. and B.A.; Formal analysis: B.A.; Data curation: B.A.; Validation: B.A.; Writing – original draft: A.B.; Writing – review & editing: A.B. and B.A.; Supervision: A.B. Both authors have read and approved the final version of the manuscript.

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Use of AI Tools

The authors declare that artificial intelligence (AI) tools were utilized solely for linguistic refinement, translation verification, and formatting compliance during the preparation of this manuscript. The analytical logic, experimental design, calculations, and scientific conclusions were entirely formulated by the human authors.

Ethics Approval / Consent
Ethical approval was not required for this study, as it involved standard non-human combustion laboratory experiments on a stationary diesel engine and did not involve human participants or live animals.

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