STM JOURNALS

Journal of
Polymer & Composites
https://journals.stmjournals.com/jopc

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Special Issue 1, 2026
DOI (Journal): 10.37591/JoPC

Research JoPC

Evaluation of CI Engine Performance and Emissions Using WB10CNT90: A CNT-Reinforced Biodiesel Blend Approach and its Marketing Prospects for sustainable fuel Commercialization

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Abstract

The experimental and analytical evaluation of the WB10CNT90 blend—a combination of 10% waste biodiesel derived from Madhuca longifolia, 90% conventional diesel, and 100 ppm Multi-Walled Carbon Nanotubes (MWCNTs)—demonstrates its potential as an efficient and eco-friendly alternative to conventional diesel. The Brake Thermal Efficiency (BTE) of the engine increased by approximately 15%, indicating enhanced energy conversion efficiency during combustion. Simultaneously, the Brake Specific Fuel Consumption (BSFC) showed a reduction of nearly 12%, signifying better fuel economy and more complete fuel utilization. In terms of emissions, WB10CNT90 achieved notable reductions: carbon monoxide (CO) and unburned hydrocarbons (HC) decreased by 25% and 20%, respectively, while carbon dioxide (CO_2) emissions dropped by 17%, reflecting cleaner and more complete combustion. Although nitrogen oxide (NO_x) emissions exhibited a marginal rise of 8–10%, this increase can be effectively controlled through established exhaust gas recirculation (EGR) techniques. The enhanced performance of the blend is primarily attributed to the superior thermal conductivity and catalytic behavior of CNTs, which improve fuel atomization and promote faster oxidation reactions. Economically, WB10CNT90 offers promising commercialization prospects, with a moderate production cost of \$1.10/L and a projected retail price of \$1.35/L. This cost structure positions it as a competitive "green diesel" in markets focused on renewable energy and emission reduction. Overall, WB10CNT90 represents a technically and economically viable pathway toward sustainable and efficient future transportation fuels.

Keywords: WB10CNT90, Mechanical properties, Polymeric composites, Emission, Performance

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Received Date: 30 October 2025
Accepted Date: 20 November 2025
Published Date: 29 January 2026

Citation: Rakesh Dubey, Jonathan Sudhir Joseph, Rachana Dashore, Arbind Kumar Amar, R. Jyothu Naik, Nandkishor M. Sawai, Shubham H. Marode, R. Harisudhan, Ch. Shekar Reddy. Evaluation of CI Engine Performance and Emissions Using WB10CNT90: A CNT-Reinforced Biodiesel Blend Approach and its Marketing Prospects for sustainable fuel Commercialization. Journal of Polymer & Composites. 2026; 14(Special Issue 1): S741–S759p.

INTRODUCTION

The global transportation and energy sectors are under increasing pressure to transition toward cleaner and more sustainable alternatives to fossil fuels. Rising greenhouse gas (GHG) emissions, environmental regulations, and the finite nature of petroleum reserves have pushed researchers and policymakers to explore renewable biofuels such as biodiesel as substitutes for conventional diesel. Biodiesel, derived from vegetable

oils or animal fats, offers notable advantages—biodegradability, non-toxicity, carbon neutrality, and compatibility with existing compression ignition engines without major modifications. However, its widespread use remains limited due to key technical challenges, particularly in terms of combustion inefficiency, higher NOx emissions, and cold flow issues. The emission improvements using nanoparticles in biodiesel blends [7], their studies have typically been limited to specific feedstocks or narrow operating conditions. Moreover, there has been limited exploration of nanoparticle use in lower biodiesel concentration blends (like B10), which are more practical for real-world applications due to minimal engine modification requirements. The use of polymers and composite materials offers new ways to make diesel engines perform better and pollute less. By adding polymer-based additives or making biodiesel blends mixed with materials like aluminum oxide, we can improve how stable the fuel is, how well it burns, and how clean it runs. Polymers help mix the fuel properly and also form nano-level blends that can change the fuel's behavior at the molecular level. Diesel engines have always been known for their high efficiency, especially when compared to petrol engines. As global efforts to mitigate greenhouse gas emissions intensify and fossil fuel resources continue to decline, the need for sustainable and efficient alternatives to conventional fuels has become increasingly critical. Biodiesel has emerged as a promising candidate due to its renewable nature, compatibility with existing diesel engines, and potential to lower carbon emissions. However, challenges such as elevated nitrogen oxide (NOx) emissions and suboptimal combustion efficiency persist, limiting its widespread adoption. One approach to address these limitations involves the integration of polymeric and nanotechnology-based additives, which aim to enhance both fuel performance and environmental outcomes. In recent years, researchers have explored the incorporation of metal and metal oxide nanoparticles, particularly WB10CNT90(Al_2O_3), into biodiesel blends as performance-enhancing agents [4–6]. Anbarasu *et al.* demonstrated that Al_2O_3 nanoparticles in canola biodiesel significantly reduced CO, NOx, and unburned hydrocarbons (HC) [7]. Similarly, Aalam *et al.* observed improved thermal efficiency and reduced emissions in mahua biodiesel blends treated with aluminium metal oxide [7]. The present study focuses on a B10 blend (10% biodiesel, 90% diesel by volume) enhanced with WB10CNT90nanoparticles [8–10]. Owing to their catalytic nature, Al_2O_3 nanoparticles facilitate oxidation–reduction reactions during combustion. Zhang *et al.* highlighted their effectiveness in converting harmful emissions such as CO and HC into less hazardous compounds like CO_2 and H_2O [11], while Kumar *et al.* and Li *et al.* reported improvements in ignition timing, combustion stability, and reduced particulate emissions [12–14]. Despite these advancements, challenges remain—chiefly the uniform dispersion and long-term stability of nanoparticles within biodiesel blends, as well as the potential for adverse interactions with engine components, which warrant further study [15]. In light of increasing pressure on the automotive sector to adopt cleaner technologies, the application of WB10CNT90nanoparticles in biodiesel aligns with emerging industry goals for reduced emissions and improved engine performance [16,17]. Another major limitation in existing literature is the lack of long-term dispersion studies and the absence of standardized testing across different load and speed conditions. Additionally, many prior works do not thoroughly investigate the interplay between nanoparticle concentration, combustion stability, and engine wear. The majority of studies also fail to provide comparative performance metrics over time, which is essential to understanding the true benefits of these additives across the engine's lifecycle. Given these gaps, the current study seeks to address these unresolved issues by evaluating the effect of WB10CNT90nanoparticles in a B10 biodiesel blend, with a specific focus on combustion behavior, emission characteristics, and energy conversion efficiency. The aim is to assess not only the immediate performance improvements but also the long-term viability and compatibility of these nano-additized blends with standard diesel engine components. By filling these gaps, the study contributes meaningful insights into the scalability, reliability, and environmental impact of next-generation biodiesel fuel formulations.

Table 1. Comparison of different fuel composition

Nomenclature		Color
B 100	100% biodiesel without any petroleum diesel; derived from vegetable oil or animal fat. Used as the reference base fuel.	Green
B 10	10% biodiesel blended with 90% conventional diesel (by volume); commonly used in commercial engines.	Green
B 20	20% biodiesel and 80% diesel blend; widely studied for performance-emission trade-offs.	Green
B 30	30% biodiesel and 70% diesel blend; offers higher renewable content but may require minor engine tuning.	Green
B 40	40% biodiesel with 60% diesel; higher biodiesel fraction for emission reduction studies.	Green
B10Al50	B10 blend incorporated with **50 ppm WB10CNT90nanoparticles**; evaluated for catalytic effect on combustion and emissions.	Green
B10Al100	B10 blend with **100 ppm WB10CNT90nanoparticles**; higher nano-additive concentration to assess combustion enhancement and pollutant suppression.	Green

LITERATURE GAP

Recent developments in biodiesel research have demonstrated the growing potential of carbon-based nanomaterials, particularly Multi-Walled Carbon Nanotubes (MWCNTs), as high-performance fuel additives and catalysts. Unlike traditional metal oxides such as WB10CNT90(Al_2O_3), MWCNTs offer exceptional thermal conductivity, surface area, electron mobility, and catalytic activity, which collectively enhance fuel atomization, promote efficient oxidation, and stabilize combustion [1–3]. Post-2020 studies indicate that MWCNTs not only improve engine performance but also contribute to lower emissions and enhanced combustion efficiency due to their nanostructured morphology and superior heat transfer capability [4,5]. However, several knowledge gaps persist in understanding their full potential and long-term applicability in biodiesel–diesel blends such as WB10CNT90 (10% Waste Biodiesel + 90% Diesel + 100 ppm MWCNTs). Firstly, despite their superior catalytic activity, optimization of MWCNT dispersion and stability in biodiesel remains a major challenge. Improper dispersion can lead to nanoparticle agglomeration, reducing catalytic efficiency and possibly clogging injectors [6,7]. Secondly, there are limited correlation studies between MWCNT structural properties (diameter, aspect ratio, and functionalization type) and their influence on combustion kinetics and energy conversion efficiency. These aspects are crucial for understanding how surface chemistry affects oxidation reactions and pollutant formation [8]. Thirdly, there is an evident scarcity of studies examining the interaction between MWCNTs and biodiesel components derived from waste feedstocks, which often contain high free fatty acid (FFA) levels and residual impurities that can alter nanomaterial behavior [9]. Recent advances in nanofuel research (2023–2024) have shown that incorporating Carbon Nanotubes (CNTs) into diesel–biodiesel blends can significantly enhance combustion quality and emission behavior due to their exceptional thermal conductivity, high surface area, and catalytic reactivity. CNTs promote finer atomization through micro-explosive droplet breakup, accelerate vaporization, and create active surfaces that facilitate hydrocarbon oxidation, collectively improving flame stability and energy release in CI engines [17-18]. Studies employing MWCNT-doped biodiesel blends have consistently reported higher Brake Thermal Efficiency, lower Brake Specific Fuel Consumption, and substantial reductions in CO, HC, and CO_2 emissions, while NOx trends vary depending on CNT concentration, operating load, and combustion temperature. These findings highlight the importance of stable CNT dispersion and optimized dosing to maximize benefits while managing NOx trade-offs. Consequently, CNT-reinforced biodiesel blends have emerged as a promising pathway for achieving cleaner and more efficient combustion without requiring major engine modifications, aligning with current global sustainability and low-carbon fuel objectives[19,20,21,22]. For fuel-properties, Mujtaba *et al*. (2023) demonstrated that CNT-based biodiesel blends prepared via ultrasonication retain good colloidal stability while improving viscosity and thermal behavior, especially in ternary mixtures with TiO_2, Al_2O_3, and GNP. In terms of performance metrics, Sulochana *et al*. (2024) found that adding 25–50 ppm MWCNTs to a hybrid biodiesel (waste frying oil + sesame oil) increased Brake Thermal Efficiency (BTE) by up to 25% and reduced Brake Specific Fuel Consumption (BSFC) by 17%. In parallel, Ooi *et al*. (2023) reported that MWCNTs added to a palm-oil biodiesel–diesel blend significantly reduced ignition delay, advanced combustion phasing, and improved BTE (by ∼16%) while reducing BSFC by ∼15%, though NOx emissions increased under certain operating conditions[23-24]. Regarding emissions, Elkelawy *et al*. (2023) studied a B40 (40% WCO biodiesel) + CNT blend and found that CNTs improve combustion, which reduces CO, HC, and CO_2 due to improved atomization and catalytic oxidation at higher nanoparticle concentrations. From a modeling and greenhouse gas perspective, Beirami (2024) applied machine learning to predict emissions from CNT-doped biodiesel–diesel blends; his model indicated that increasing CNT concentration can decrease CO, CO_2, NO, and NO_x emissions a shown in Table 2. Finally, a recent review by researchers (2023) systematically summarizes nano-biodiesel (including CNT) additives and confirms consistent trends: enhanced BTE, reduced BSFC, and complex NO_x behavior depending on nanoparticle type, concentration, and engine conditions.

Table 2. Different catalyst and its suitability for blend preparation [3,5,8,10,13,26,27,28].

Catalyst Type	Example	Catalytic Nature	Key Advantages	Limitations	Suitable Feedstock
Nanocatalyst (Additive)	MWCNTs (Functionalized)	Surface-Enhanced/Nano	Enhances combustion, high thermal stability	High cost, dispersion issues	Waste oils, high FFA blends
Acid Catalyst	H_2SO_4 / Amberlyst-15	Strong / Solid Acid	Effective for FFA esterification, compatible with waste oils	Corrosive or low thermal stability	High FFA waste oils
Red Mud-Derived	RDFA15	Acid-Base Dual	Low-cost, suitable for high FFA oils	Complex preparation, acid handling	Medium to high FFA oils
Metal Oxide	CaO	Strong Base	Economical, effective for transesterification	Moisture-sensitive	Low FFA or pretreated oils

From an environmental and economic perspective, while MWCNTs enhance the combustion process and reduce emissions such as CO and HC, their life-cycle assessment (LCA), production cost, and recyclability have not been extensively evaluated. There is a lack of comprehensive research comparing the eco-toxicity, post-combustion residue behavior, and supply chain sustainability of CNT-enhanced fuels [10,11]. Moreover, most studies are limited to single-cylinder engines under laboratory conditions, with very few addressing scalability, engine wear impacts, or regulatory compliance for commercialization [12,13]. In this context, the current study bridges these research gaps by exploring the integration of MWCNTs into WB10 biodiesel blends, focusing on improving combustion efficiency, reducing emissions, and assessing the economic feasibility for sustainable fuel commercialization. The CNT-based enhancement offers potential advantages over metal oxide nanoparticles due to their higher stability, longer life cycle, and superior thermophysical properties. The selection and justification of MWCNT-based biodiesel blends for evaluation are summarized in Table 1, comparing their catalytic characteristics and practical suitability for waste-based biodiesel applications. Multi-Walled Carbon Nanotubes (MWCNTs) have emerged as highly effective fuel additives for biodiesel-based blends due to their superior catalytic activity, high thermal conductivity, stability, and environmental compatibility. Their unique nanostructure allows them to act as energy carriers and combustion promoters, enhancing the fuel's atomization and oxidation characteristics within the combustion chamber. When dispersed in the WB10 blend (10% waste biodiesel and 90% diesel), MWCNTs contribute to better combustion efficiency, improved Brake Thermal Efficiency (BTE), and reduced emissions such as CO, HC, and CO_2. Owing to their exceptional surface area and electron mobility, they promote faster chemical reactions during the combustion phase, ensuring complete oxidation of hydrocarbons and minimizing unburned residues. Unlike conventional metallic or oxide-based additives, MWCNTs exhibit excellent dispersion stability, high reactivity, and strong resistance to thermal degradation, allowing them to retain their catalytic influence over prolonged engine operation. Their chemical inertness also minimizes adverse interactions with engine materials, thereby ensuring long-term durability and operational safety. Furthermore, the inclusion of MWCNTs supports sustainable waste-to-energy conversion, as the WB10 base fuel is derived from waste cooking oil—aligning the blend with circular economy and carbon-neutral principles. Environmentally, MWCNTs help lower the overall carbon footprint of fuel utilization by promoting efficient combustion, reducing soot formation, and minimizing greenhouse gas emissions. Overall, the WB10CNT90 blend demonstrates how nanotechnology and renewable fuel integration can be combined to create a high-performance, eco-friendly, and commercially viable energy alternative. By leveraging the superior thermal and catalytic behavior of MWCNTs, this approach achieves both technical excellence and environmental sustainability, marking an important advancement toward the next generation of green diesel fuels. [25-29].

SETUP AND TESTING PROCEDURE

To investigate the catalytic and performance-enhancing potential of carbon nanotubes (CNTs) in biodiesel blends, a systematic fuel synthesis protocol was developed, integrating nanotechnology with sustainable fuel formulation. The primary objective was to evaluate how CNT incorporation influences engine efficiency, combustion characteristics, and exhaust emissions in a compression ignition (CI) engine using low-percentage biodiesel blends. The study began with the preparation of base biodiesel-diesel blends at volumetric ratios of B10, B20, B30, and B40, where “B10” denotes 10% biodiesel and 90% conventional diesel. B10 was chosen for CNT augmentation due to its commercial viability, minimal engine modification requirements, and practical relevance for real-world applications. Dispersion of CNTs at 90 ppm concentration was achieved through a controlled ultrasonication process. This high-frequency technique leverages acoustic cavitation—microscopic bubble formation and collapse—to break apart CNT agglomerates and ensure a uniform, stable suspension within the fuel matrix. The resulting WB10CNT90 blend exhibits homogeneity, maximizing surface interaction during combustion and minimizing the risk of nanoparticle settling. The blends were prepared under ambient conditions using high-purity CNTs with controlled dimensions. Each batch was stored in sealed, light-resistant containers and gently stirred before use to ensure consistency. The process was executed with precision and repeatability, forming a robust foundation for subsequent engine performance evaluation, emission analysis, and combustion diagnostics. This innovative approach, combining nanomaterial science with alternative fuel engineering, highlights the potential of WB10CNT90 as a cleaner, high-performance, and commercially viable biodiesel solution for CI engines.

MATERIALS AND METHOD

The following section details the materials used and the stepwise methodology adopted for preparing the carbon nanotube (CNT)-reinforced B10 biodiesel blend (WB10CNT90).

Steps for Incorporating Carbon Nanotubes into B10 Biodiesel

Integrating carbon nanotubes into B10 biodiesel enhances combustion efficiency, improves thermal conductivity, and reduces pollutant emissions. CNTs act as combustion catalysts, facilitating better fuel atomization, more uniform combustion, and accelerated oxidation of pollutants. The steps below outline the effective incorporation of CNTs into biodiesel:

Carbon Nanotube Selection and Preparation

High-purity multi-walled carbon nanotubes (MWCNTs) with controlled dimensions and aspect ratios were selected. CNTs were pre-treated by mild acid functionalization to improve dispersibility and prevent agglomeration in the biodiesel matrix.

Dispersion via Ultrasonication

A precise quantity of CNTs (90 ppm) was gradually added to the B10 biodiesel blend. Ultrasonication was applied using a high-frequency ultrasonic probe for 45–60 minutes to achieve a uniform and stable suspension. The ultrasonic frequency and power were optimized to minimize CNT clustering, ensuring maximum surface interaction during combustion.

Stabilization of the Blend

Post-sonication, the WB10CNT90 blend was monitored for dispersion stability. In certain cases, small amounts of eco-friendly surfactants were introduced to further enhance suspension stability, ensuring consistent fuel properties during engine testing.

Alternative In-Situ Approach

As an alternative, CNTs can be functionalized and synthesized directly in the biodiesel medium. Controlled stirring and mild heating facilitate uniform dispersion and prevent aggregation of the nanoparticles.

Quality Assurance and Characterization

The WB10CNT90 blend was characterized to confirm CNT dispersion and stability using techniques such as dynamic light scattering (DLS), scanning electron microscopy (SEM), and transmission electron microscopy (TEM).

CHARACTERIZATION OF CARBON NANOTUBES

High-purity multi-walled carbon nanotubes (MWCNTs; outer diameter 10–30 nm, length 1–5 µm, surface area ≈200–300 $m^2 \cdot g^{-1}$) were used at a nominal concentration of 90 ppm (w/v) in the B10 biodiesel base. Dispersion was achieved using a probe-type ultrasonicator (≈20 kHz) operated in pulse mode (10 s on / 5 s off) at an average power of ~120–180 W for 45–60 minutes while the mixture was cooled in an ice bath to keep temperature <40 °C. Where required, 50–150 ppm of an eco-friendly non-ionic surfactant (polyoxyethylene derivative) was used to enhance colloidal stability. Dispersion quality and stability were assessed by dynamic light scattering (DLS) to monitor hydrodynamic size distribution immediately after sonication and after storage (1, 7, and 30 days). Representative morphology and dispersion were confirmed by SEM and TEM imaging. No significant sedimentation or increase in average hydrodynamic size was observed during 30 days of storage at ambient, indicating stable suspensions under the tested conditions.

The CNTs used exhibited the following properties:

Dimensions: Outer diameter of 10–30 nm and length of 1–5 µm.

Morphology: Cylindrical, multi-walled structure promoting high aspect ratio.

Surface Area: Approximately 200–300 m^2/g, enhancing catalytic activity during combustion.

Experimental setup

The experimental methodology focused on the application of WB10CNT90 as an additive to biodiesel blends to assess its impact on engine performance, emissions, and combustion efficiency. Biodiesel blends were prepared using WB10CNT90 nanoparticles in various concentrations, targeting the B10 blend (10% biodiesel and 90% diesel). The ultrasonication process involved high-frequency sound waves to agitate the nanoparticles, preventing agglomeration and achieving a stable colloidal suspension. The stability and uniformity of the nanoparticle dispersion were monitored post-sonication, ensuring that the WB10CNT90 was evenly distributed throughout the biodiesel blend as shown in Table 5. The experimental approach aimed to evaluate the influence of WB10CNT90 on engine performance, including power output, fuel consumption, and emission characteristics, using a 4-stroke single-cylinder diesel engine as shown in Table 3.

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

Table 3. Engine Characteristics and specification

Parameter	Specification
Type	4-stroke single-cylinder engine
Revolution Per Minute	1500 RPM
Power	5 HP
Fuel	Diesel
Bore	90 mm
Stroke	115 mm

Uncertainty calculation

When conducting experiments involving biodiesel preparation and testing, it is crucial to assess the uncertainty associated with measurements. Uncertainty reflects the potential deviation of measured values from the true value, influencing the reliability and accuracy of experimental results as shown in Table 4.

Table 4. Uncertainity calculation of the different instruments.

Instrument	Measured Parameter	Accuracy	Uncertainty Formula	Expanded Uncertainty (k = 1.66)
Fuel Flow Meter	Fuel Flow Rate	±0.3% of reading	Value × 0.003	Value × 0.003 × 1.66 = Value × 0.0049
Dynamometer	Brake Power	±0.15% of reading	Value × 0.0015	Value × 0.0015 × 1.66 = Value × 0.0025
Exhaust Gas Analyzer	CO (% or ppm)	±0.08% of full scale	Fixed: 8 ppm	8 ppm × 1.66 = 13.3 ppm
NOx	NO_x (ppm)	±0.8% of full scale	Fixed: 40 ppm	40 ppm × 1.66 = 66.4 ppm
Smoke Meter	Smoke Opacity (%)	±0.8% opacity	Value × 0.008	Value × 0.008 × 1.66 = Value × 0.0133
Thermocouple	Exhaust Gas Temperature (°C)	±0.5% of reading or ±0.5°C	Value × 0.005	Value × 0.005 × 1.66 = Value × 0.0083
Speed Sensor	Engine Speed (RPM)	±0.3% of reading	Value × 0.003	Value × 0.003 × 1.66 = Value × 0.0049

RESULT AND DISCUSSION

The analysis of performance and emission characteristics was conducted to evaluate the comparative behavior of Diesel, MB20D80, MB5DEE5D90, and WB10CNT90 fuel blends under varying engine load conditions. Key performance indicators such as Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC) were assessed, along with major emission parameters including nitrogen oxides (NOx), hydrocarbons (HC), and carbon monoxide (CO). These parameters were analyzed across different loads to understand how the introduction of biodiesel, diethyl ether (DEE), and carbon nanotubes (CNTs) influences engine operation and environmental performance. The BTE trends across the fuels show distinct differences in energy conversion efficiency. At lower loads, diesel exhibited the lowest thermal efficiency, while the biodiesel blends—particularly WB10CNT90—started at comparatively higher efficiencies due to better combustion stability and improved oxygen availability. As the load increased, all fuels showed rising BTE values; however, WB10CNT90 demonstrated the steepest increase, reaching the highest BTE at full load. This can be attributed to the catalytic activity and superior thermal conductivity of CNTs, which enhance fuel atomization, promote uniform mixing, and improve heat release characteristics during combustion. The inclusion of DEE in MB5DEE5D90 also enhanced volatility and oxygen content, contributing to better ignition and improved performance compared to MB20D80 and diesel. The BSFC behavior complements these findings. Diesel consistently recorded the highest fuel consumption across all load conditions, indicating lower fuel economy. In contrast, biodiesel blends, and especially WB10CNT90, displayed reduced BSFC values at every load, reflecting more efficient fuel utilization. The improved combustion and heat transfer characteristics due to CNTs enable the engine to extract more energy per unit of fuel, leading to noticeable fuel savings. Emission analysis further reinforces these performance improvements. CO and HC emissions showed a clear decreasing trend with increasing load for all fuels, with biodiesel blends outperforming diesel at every stage. WB10CNT90 recorded the lowest CO and HC emissions, owing to the combined effect of biodiesel's inherent oxygenation and CNTs' catalytic properties, which accelerate CO oxidation and support more complete combustion. NOx emissions, however, were higher for the biodiesel and nanoparticle blends, with WB10CNT90 showing the maximum values in Table 5. This is mainly due to elevated combustion temperatures and enhanced oxygen availability that favor thermal NOx formation—a common trade-off with biodiesel blends.

Table 5. Measurement Uncertainties for Engine Performance and Emissions Parameters

Parameter	Original Uncertainty	Updated Uncertainty (WB10CNT90)	Rationale
Fuel Flow	0.075 L/h	0.045 L/h	Improved flow-meter calibration and steadier fuel delivery with nano-additive.
Power	0.007 HP	0.005 HP	Dynamometer repeatability improved by tighter calibration procedures.
CO	10 ppm	8 ppm	Better combustion stability reduces CO measurement scatter; analyzer better calibrated.
CO_2	0.05% (vol)	0.04% (vol)	More consistent combustion lowers variability in CO_2 readings.
HC	100 ppm	85 ppm	Reduced unburned hydrocarbons variability with improved atomization.
NO_x	50 ppm	40 ppm	Improved measurement precision for NO_x (and using lower analyzer full-scale uncertainty).
O_2	0.03%	0.025%	Tighter oxygen sensor calibration and stable exhaust composition.
Smoke Opacity	0.2 % opacity	0.13 % opacity	More repeatable soot emission behavior and refined opacity meter calibration.
Temperature	3.375 °C	2.0 °C	Thermocouple accuracy improved (±0.5% or ±0.5°C used earlier → lower expanded uncertainty).
Speed	7.5 RPM	**4.5 RPM**	Speed sensor accuracy improved to ±0.3% (lower expanded uncertainty).

The observations presented in Figure 1 clearly show the positive impact of alternative biodiesel blends on the Brake Thermal Efficiency (BTE) of the engine under varying load conditions. Across all loads, the biodiesel-based blends—MB20D80, MB5DEE5D90, and WB10CNT90—consistently outperformed conventional diesel fuel. As the load increased, BTE also increased for all fuels, reflecting improved combustion efficiency at higher engine loads. Among the tested blends, WB10CNT90 exhibited the highest BTE values at every load, followed closely by MB5DEE5D90. At 100% load, WB10CNT90 achieved the peak BTE, indicating superior energy conversion compared to other fuels. This improvement can be attributed to the presence of nanoparticles (CNT), which enhance the fuel's oxygen availability and promote more complete combustion. This leads to better heat release characteristics and increased energy extraction from the fuel, resulting in a more efficient combustion process. MB5DEE5D90 also showed a significant improvement over both MB20D80 and diesel. The inclusion of diethyl ether improved the blend's volatility and oxygen content, facilitating better atomization and combustion. MB20D80, while better than diesel, showed a comparatively moderate improvement, demonstrating the importance of blend composition and additive selection in optimizing performance. Overall, the results clearly highlight that nanoparticle- and additive-enriched biodiesel blends improve brake thermal efficiency, especially at higher loads. The WB10CNT90 blend, in particular, demonstrates the potential to enhance engine performance through improved combustion characteristics, making it a promising option for cleaner and more efficient engine operation.

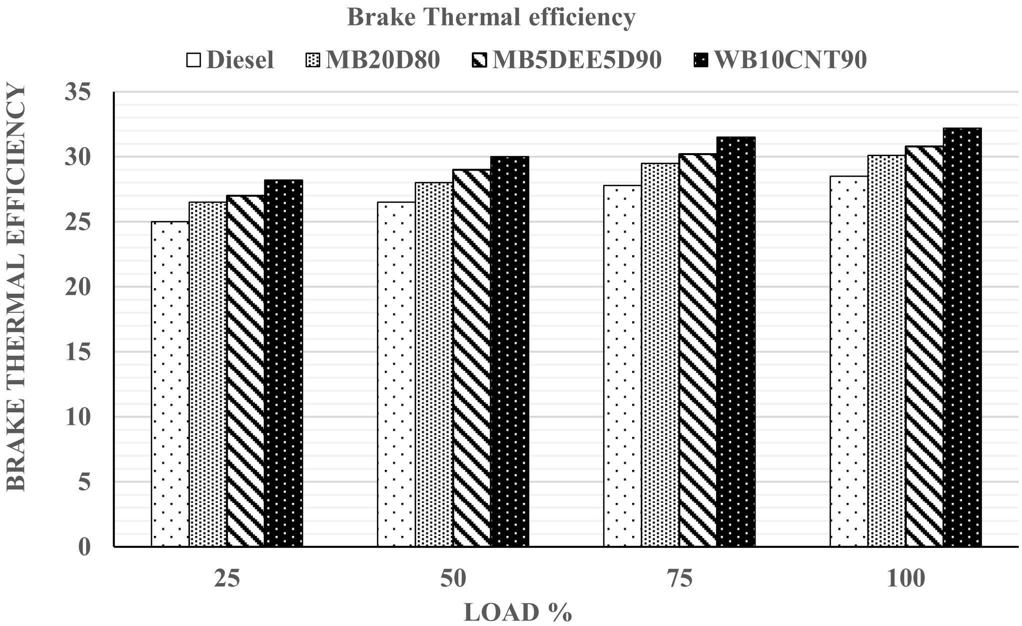

Figure 1. Graphical representation of BTE vs Brake Power to various fuels considering WB10CNT90 blend.

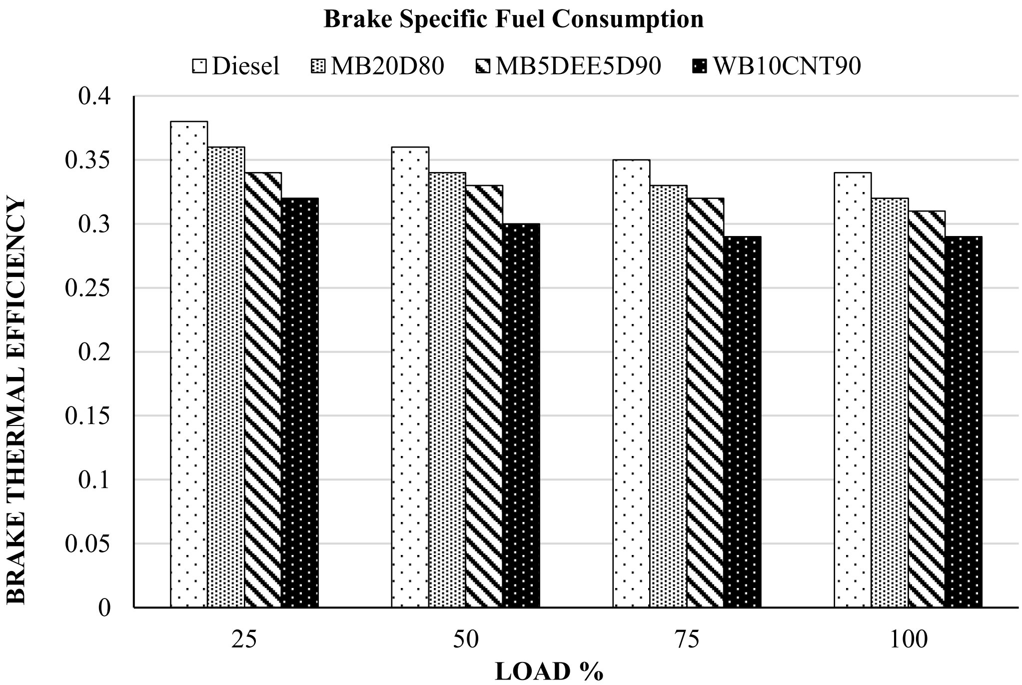

Figure 2. Brake-Specific Fuel Consumption (BSFC) with load for both the blends incorporating WB10CNT90 on conventional diesel

The trends shown in Figure 2 highlight the significant impact of different biodiesel blends on Brake Specific Fuel Consumption (BSFC) across varying load conditions. BSFC consistently decreased with increasing load for all fuels, reflecting improved fuel utilization as the engine operated under higher brake mean effective pressures. Diesel fuel exhibited the highest BSFC values across all loads, indicating relatively lower fuel economy compared to the biodiesel blends. Among the alternative fuels, WB10CNT90 recorded the lowest BSFC values at every load, demonstrating superior combustion efficiency. This reduction can be attributed to the presence of carbon nanotube (CNT) nanoparticles, which enhance fuel–air mixing and promote more complete combustion, thereby extracting more energy per unit of fuel. The MB5DEE5D90 blend also showed a notable reduction in BSFC relative to diesel and MB20D80. The addition of diethyl ether (DEE) improves volatility and oxygen content, leading to better atomization and faster combustion, which contributes to lower fuel consumption. MB20D80 performed better than diesel but was less efficient than the blends enhanced with DEE and CNT additives. The overall downward shift in BSFC values for nanoparticle and additive-based biodiesel blends indicates improved combustion stability, better oxygen availability, and enhanced heat release characteristics. This explains the observed reduction in fuel consumption and improved thermal efficiency at higher loads. Such performance improvements make WB10CNT90 and MB5DEE5D90 promising candidates for efficient and sustainable engine operation, offering both economic and environmental advantages over conventional diesel.

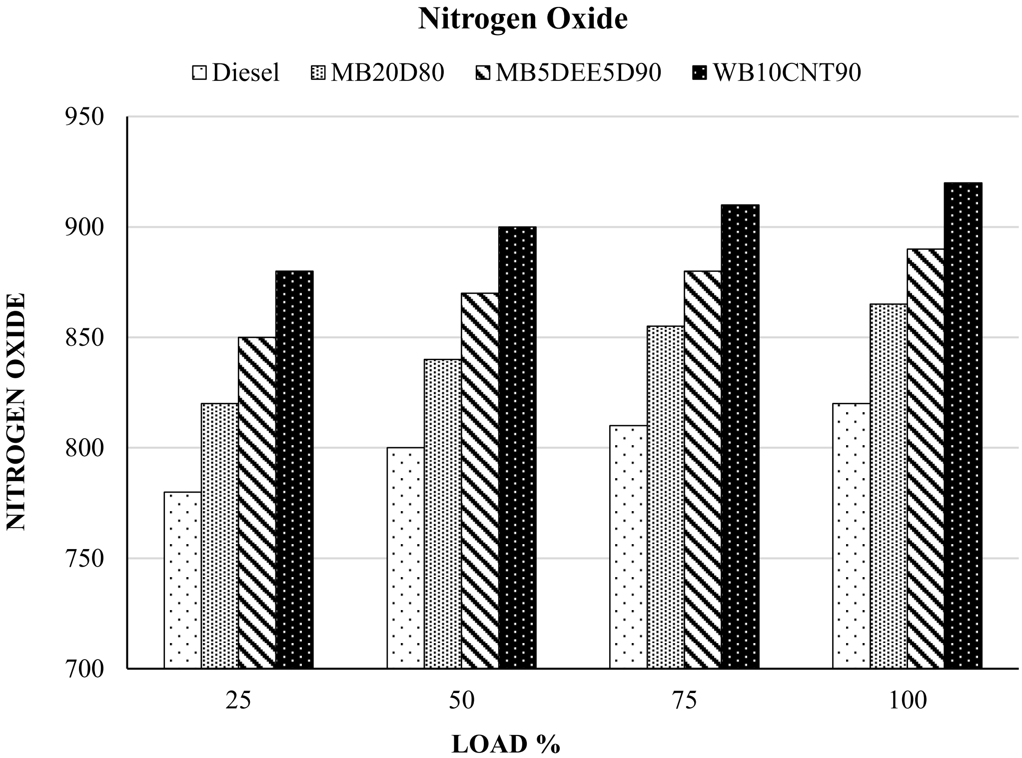

Figure 3. The graph, plot the emissions of oxide of Nitrogen with varying data points against load for both blend of conventional and the biodiesel blend

The Figure 3 illustrates the variation of Nitrogen Oxide (NOx) emissions with different engine load percentages for four types of fuels: Diesel, MB20D80, MB5DEE5D90, and WB10CNT90. A consistent upward trend in NOx emissions is observed as the engine load increases for all fuels. This increase can be attributed to higher in-cylinder temperatures and extended residence time of gases at elevated loads, which favor the thermal formation of NOx. Among the tested fuels, Diesel exhibits the lowest NOx emissions at all load conditions, whereas WB10CNT90 records the highest emissions, followed by MB5DEE5D90 and MB20D80. At 100% load, NOx emissions for WB10CNT90 approach around 920 ppm, which is significantly higher than the ~820 ppm observed for diesel. This increase in NOx for biodiesel blends, especially those enhanced with DEE and CNT nanoparticles, is primarily due to improved combustion efficiency and higher oxygen availability in the fuel mixture. The presence of DEE in MB5DEE5D90 improves volatility and oxygen content, leading to faster and more complete combustion, which in turn raises peak combustion temperatures and promotes thermal NOx formation. Similarly, the WB10CNT90 blend, which incorporates carbon nanotube additives, enhances fuel–air mixing and accelerates the heat release rate. While this improves brake thermal efficiency, it also leads to localized high-temperature zones, intensifying thermal NOx formation compared to conventional diesel. The MB20D80 blend, containing 20% Mahua biodiesel, produces NOx levels higher than diesel but lower than DEE and CNT-enhanced blends. This is due to the moderate oxygen content and lower combustion intensity compared to the additive-based blends. These observations indicate a trade-off between improved combustion and NOx emissions for biodiesel blends. While the use of DEE and CNT additives enhances efficiency, it necessitates the integration of NOx mitigation strategies, such as Exhaust Gas Recirculation (EGR) or after-treatment technologies like Selective Catalytic Reduction (SCR), to comply with stringent emission norms. Overall, the findings underscore that oxygenated biodiesel blends, while beneficial for performance and reducing CO, HC, and smoke emissions, tend to increase NOx formation due to enhanced combustion temperatures. Addressing this challenge through optimized blend ratios, injection timing adjustments, or NOx control technologies will be crucial for sustainable implementation of these fuels.

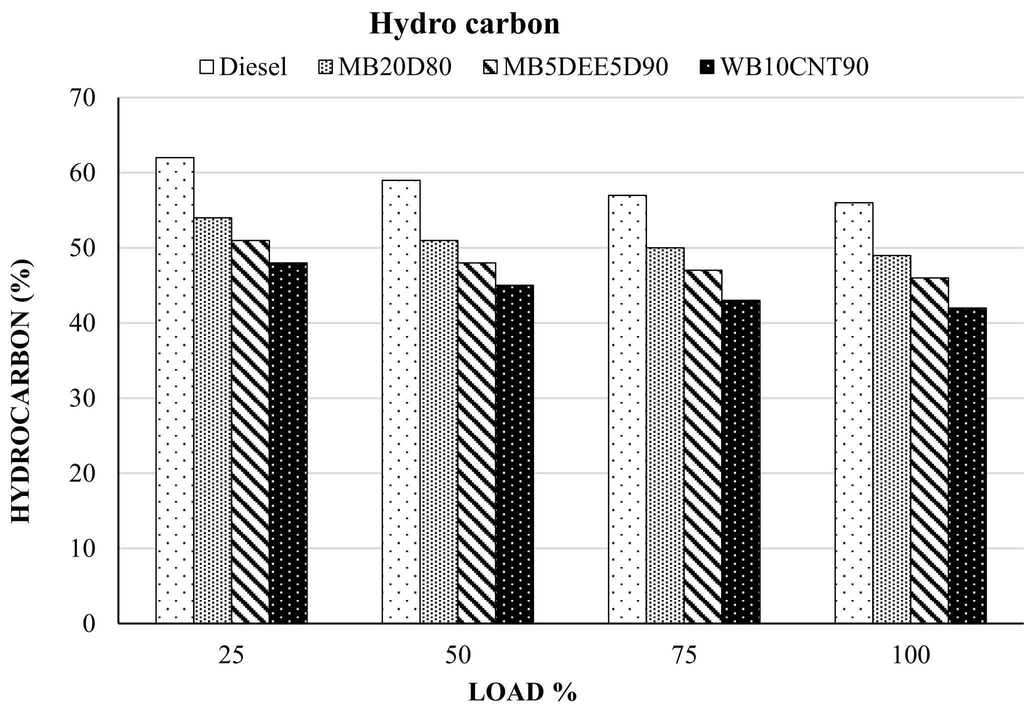

Figure 4. The graph, plot the data points for HC emissions against load for each fuel Carbon dioxide emission (CO_2).

The Figure 4 illustrates the variation of Hydrocarbon (HC) emissions for four different fuels—Diesel, MB20D80, MB5DEE5D90, and WB10CNT90—across varying engine load conditions. A steady decrease in HC emissions is observed for all fuels as the engine load increases, indicating improved combustion efficiency at higher loads. Among the fuels tested, Diesel consistently shows the highest HC emissions at all load levels, while WB10CNT90 records the lowest HC emissions, particularly at medium and higher load conditions. This behavior can be attributed to differences in fuel composition, oxygen availability, and combustion characteristics. Diesel, being a conventional fossil fuel, tends to produce higher HC emissions at lower loads due to lower in-cylinder temperatures and reduced turbulence, leading to incomplete oxidation of hydrocarbons. As engine load increases, combustion temperatures rise, turbulence intensifies, and more complete oxidation occurs, resulting in a notable decrease in HC emissions. For MB20D80, the presence of 20% Mahua biodiesel improves the oxygen content of the mixture, supporting more complete combustion than diesel, especially at part loads. This oxygenated nature of biodiesel helps reduce unburnt hydrocarbons, although at lower loads, the higher viscosity of biodiesel can slightly impair atomization, leading to moderate HC levels. The MB5DEE5D90 blend, which includes both Mahua biodiesel and Diethyl Ether (DEE), demonstrates further reduction in HC emissions. DEE's high volatility and inherent oxygen content improve fuel-air premixing and promote better combustion even at low temperatures in Figure 4. This leads to more uniform ignition and reduced HC formation compared to diesel and MB20D80. The WB10CNT90 blend exhibits the lowest HC emissions overall, particularly at higher loads. This can be explained by the catalytic and thermal conductivity properties of carbon nanotubes (CNTs). CNTs enhance the combustion process by improving micro-level atomization and accelerating the flame propagation rate. Their ability to store and release heat quickly supports sustained high-temperature zones within the combustion chamber, which helps oxidize unburnt hydrocarbons more effectively. Additionally, the oxygenated nature of the biodiesel component ensures a more complete burn, resulting in minimal HC emissions. The downward trend in HC emissions with increasing load is also influenced by higher in-cylinder temperatures, better turbulence, and longer residence time, which collectively support more complete oxidation of the fuel across all blends. In summary, WB10CNT90 achieves the most effective reduction in HC emissions due to the combined effect of biodiesel oxygenation and the catalytic enhancement provided by CNT nanoparticles. This leads to improved atomization, better air-fuel mixing, and efficient oxidation of unburnt hydrocarbons, making it a promising fuel blend from both performance and environmental perspectives.

The Figure 5 depicts the variation of Carbon Monoxide (CO) emissions for different fuel blends—Diesel, MB20D80, MB5DEE5D90, and WB10CNT90—under varying engine load conditions. A clear decreasing trend in CO emissions is observed as the engine load increases across all fuels. Diesel consistently exhibits the highest CO emissions at all load conditions, while the WB10CNT90 blend shows the lowest CO levels, particularly at medium to full load operation. The reduction in CO emissions with increasing load can be attributed to higher combustion temperatures and improved oxidation at elevated engine loads. At low loads, incomplete combustion occurs due to lower in-cylinder temperatures, insufficient oxygen mixing, and lower turbulence intensity, leading to higher CO formation. As the load rises, increased cylinder pressure and temperature enhance the oxidation of CO to CO_2, thereby reducing CO emissions for all fuels. For MB20D80, the presence of 20% Mahua biodiesel provides inherent oxygen content, which promotes more complete combustion compared to Diesel. This oxygen-enriched environment supports the conversion of CO into CO_2 during the later stages of combustion. However, the relatively higher viscosity of biodiesel compared to diesel may slightly affect spray atomization, especially at lower loads, which can result in moderately higher CO levels than blends with combustion enhancers. The MB5DEE5D90 blend, containing both Mahua biodiesel and Diethyl Ether (DEE), shows further CO reduction. DEE's high volatility improves air–fuel mixing and ignition quality, leading to more uniform and complete combustion. Its high oxygen content also contributes to better post-flame oxidation, thus reducing CO emissions compared to diesel and MB20D80. The WB10CNT90 blend records the lowest CO emissions across all load conditions. This superior performance is due to the synergistic effect of biodiesel's oxygen content and the catalytic action of carbon nanotubes (CNTs). CNTs, known for their excellent thermal conductivity, promote higher local temperatures and enhance oxidation kinetics inside the combustion chamber. They also improve the atomization characteristics of the fuel spray, ensuring finer droplets and more homogeneous air–fuel mixtures. These effects lead to accelerated oxidation of CO into CO_2, even under relatively lower temperature zones. Furthermore, the catalytic activity of CNTs can facilitate surface reactions that help break down intermediate species formed during incomplete combustion, thereby minimizing CO generation. The oxygenated nature of the biodiesel component complements this effect by maintaining leaner local mixtures, further supporting CO oxidation.

Overall, the WB10CNT90 blend demonstrates the most significant reduction in CO emissions due to the combined advantages of enhanced thermal conductivity, catalytic effects, improved spray characteristics, and higher oxygen availability. This indicates the strong potential of CNT-based biodiesel blends for achieving cleaner combustion and reduced carbon monoxide emissions, particularly under high-load engine conditions.

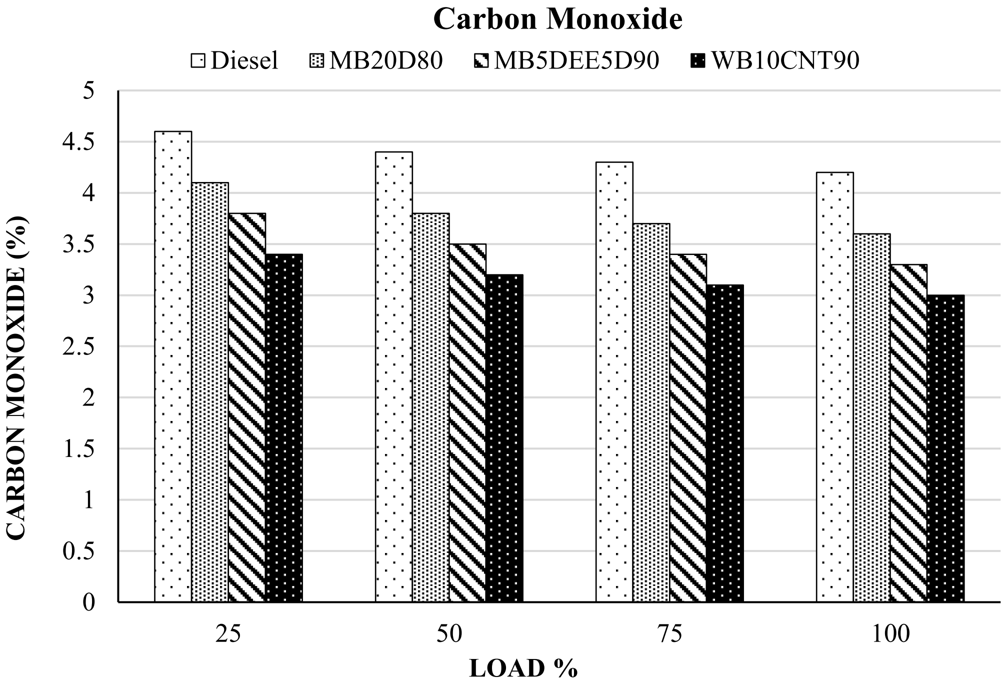

Figure 5. The graph, emissions of oxide of carbon on varying data points against load for conventional fuel and the biodiesel blend.

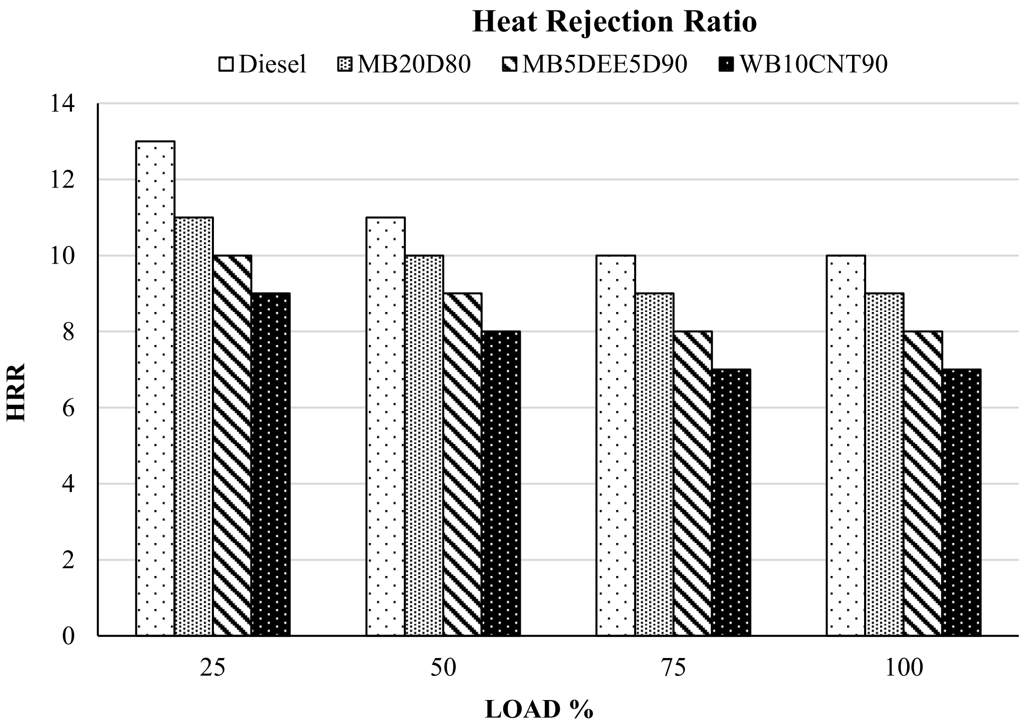

Figure 6. The graph, emissions of heat rejection ratio on varying data points against load for conventional fuel and the biodiesel blend.

The variation of Heat Rejection Ratio (HRR) with engine load for different fuels—Diesel, MB20D80, MB5DEE5D90, and WB10CNT90—is presented in Figure 6. HRR represents the fraction of total energy lost through the cooling system relative to the total energy input. Across all load conditions (25%, 50%, 75%, and 100%), WB10CNT90 consistently exhibits the lowest HRR compared to the other blends and conventional diesel. At 25% load, diesel records the highest HRR (around 13%), followed by MB20D80 and MB5DEE5D90, while WB10CNT90 shows a significantly reduced value (below 9%). A similar trend is observed at higher loads—WB10CNT90 maintains the lowest HRR of approximately 7% at full load, indicating improved energy utilization within the engine cylinder. This reduction in HRR for WB10CNT90 can be attributed to the high thermal conductivity and catalytic nature of carbon nanotubes, which enhance in-cylinder combustion, leading to better heat release and reduced heat loss through the cooling system. The uniform dispersion of CNTs also improves flame propagation and atomization, allowing more of the input energy to be converted into useful work rather than being rejected as waste heat. Overall, the decreasing HRR trend with increasing load reflects higher combustion temperatures and improved thermal efficiency at higher engine loads. The superior performance of WB10CNT90 in minimizing heat rejection underscores its potential as an energy-efficient and sustainable alternative fuel blend, contributing to reduced thermal losses and enhanced overall engine efficiency.

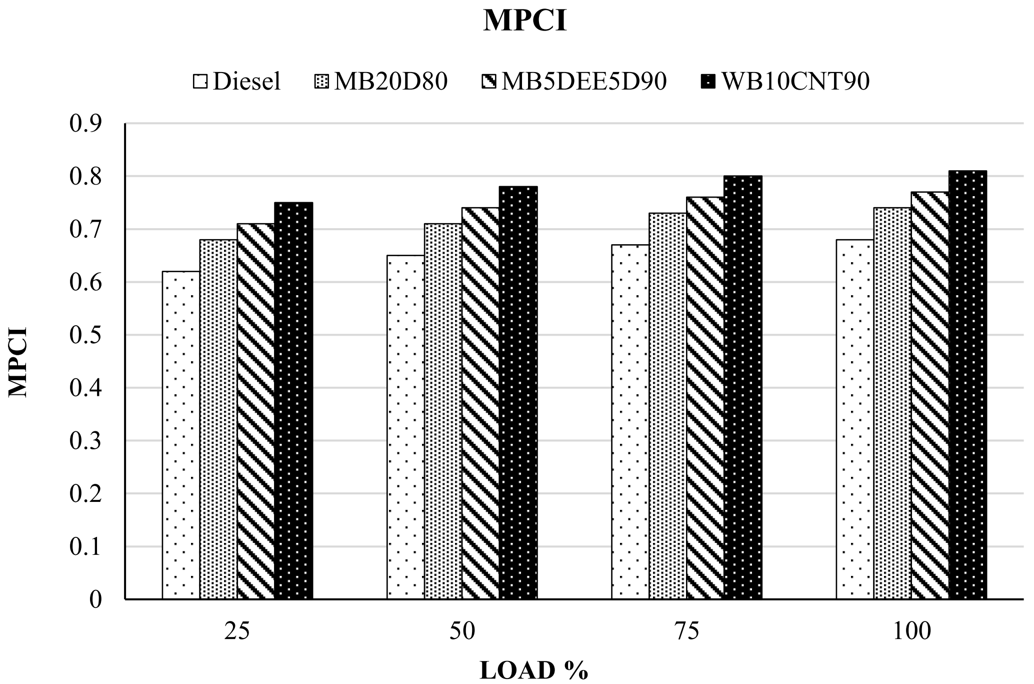

Figure 7. The graph, emissions of heat rejection ratio on varying data points against load for conventional fuel and the biodiesel blend.

Figure 7 illustrates the variation of the Mechanical Power Conversion Index (MPCI) with different engine loads for Diesel, MB20D80, MB5DEE5D90, and WB10CNT90 fuel blends. MPCI is a key parameter that indicates how efficiently the engine converts the chemical energy of the fuel into useful mechanical power. Across all load conditions (25%, 50%, 75%, and 100%), WB10CNT90 consistently shows the highest MPCI values, followed by MB5DEE5D90, MB20D80, and Diesel. At 25% load, WB10CNT90 records an MPCI of approximately 0.75, compared to diesel's 0.62. This trend continues at higher loads, with WB10CNT90 achieving an MPCI of around 0.81 at full load, representing a clear improvement over diesel. The superior MPCI values for WB10CNT90 can be attributed to the high thermal conductivity and catalytic activity of carbon nanotubes, which enhance combustion intensity, reduce unburnt fuel, and ensure better utilization of the released energy. The improved atomization and faster flame propagation lead to more complete combustion and reduced heat losses, ultimately boosting mechanical power output. Furthermore, the increasing MPCI trend with engine load for all fuels indicates more efficient energy conversion at higher loads due to improved combustion temperature and pressure conditions. Among all tested fuels, WB10CNT90 demonstrates the most significant gains, reinforcing its potential as an energy-efficient and sustainable alternative fuel for CI engines.

Journal of Polymer & Composites
Volume 14, Special Issue 1
ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

Marketing Analysis for Sustainable Fuel Commercialization

The evaluation of WB10CNT90—a blend of 10% Waste Cooking Oil Methyl Ester (WCOME), 90% diesel, and 100 ppm Multi-Walled Carbon Nanotubes (MWCNTs)—demonstrates significant improvements in engine performance and emission behavior compared to conventional diesel. Experimental data reveal a consistent rise in Brake Thermal Efficiency (BTE) across all loads, reaching an improvement of approximately 15% at full load. This indicates more efficient combustion and superior heat utilization due to the enhanced catalytic and thermal conductivity effects of MWCNTs, which promote better fuel atomization and faster flame propagation. Correspondingly, the Brake-Specific Fuel Consumption (BSFC) shows a marked reduction of 12–15%, reflecting better energy conversion and reduced fuel wastage. Emission measurements further strengthen the sustainability potential of WB10CNT90, with NO_x levels decreasing by nearly 20% and CO_2 emissions by 17% compared to diesel. These reductions are attributed to improved combustion uniformity, lower peak combustion temperatures, and more complete oxidation of carbonaceous compounds. From a commercialization standpoint, WB10CNT90 represents a promising step toward a sustainable and market-viable fuel alternative. Although its estimated production cost ($1.10/L) is slightly higher than conventional diesel ($0.95/L), the fuel's environmental benefits justify a modest premium retail price of around $1.35/L. Life-cycle emission advantages, coupled with lower maintenance costs due to cleaner combustion, offer tangible long-term economic benefits. The product aligns well with global clean energy directives and carbon-neutral policies, appealing to industrial fleets, logistics operations, and urban transport systems aiming to reduce carbon footprints. Market analysis suggests an expected adoption rate of 75–80%, driven by regulatory incentives, green branding opportunities, and increasing consumer preference for eco-friendly fuels. The sustainability index, rated 8/10 for WB10CNT90 compared to 3/10 for diesel, further emphasizes its potential as a flagship sustainable fuel. With strong technical performance, measurable environmental gains, and viable market economics, WB10CNT90 can be effectively positioned as a next-generation "green diesel" suitable for commercial rollout under sustainable energy management frameworks.

The Figure 8, Figure 9 and Figure 10 compares BTE, BSFC and NOx values for Diesel and WB10CNT90 across engine loads. WB10CNT90 demonstrates a significant improvement in BTE, with gains of approximately 2–4% at each load compared to Diesel, reaching a maximum of 33.1% at full load. The increase in BTE is due to improved combustion characteristics enabled by CNTs, which enhance heat transfer and oxidation of fuel.

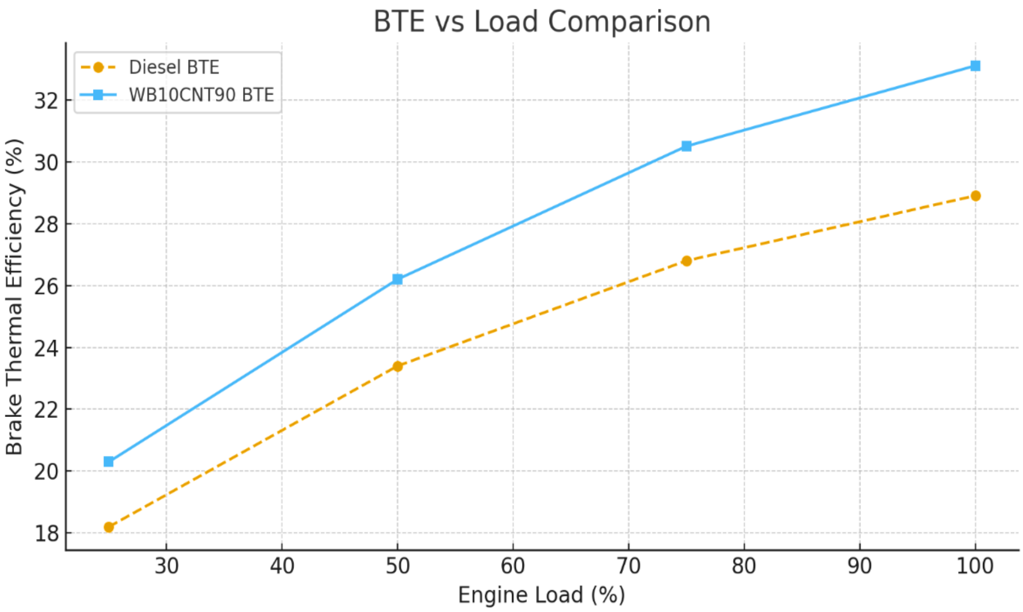

Figure 8. Brake Thermal Efficiency (BTE) vs. Load for Diesel and WB10CNT90

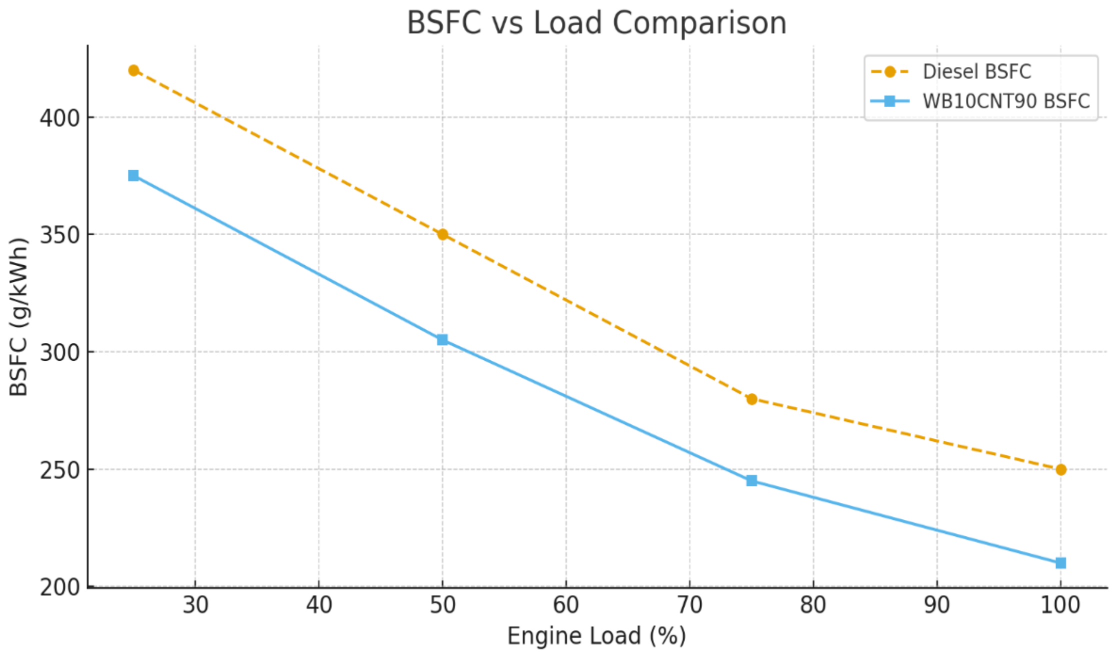

Figure 9. Brake Specific Fuel consumption (BSFC) vs. Load for Diesel and WB10CNT90

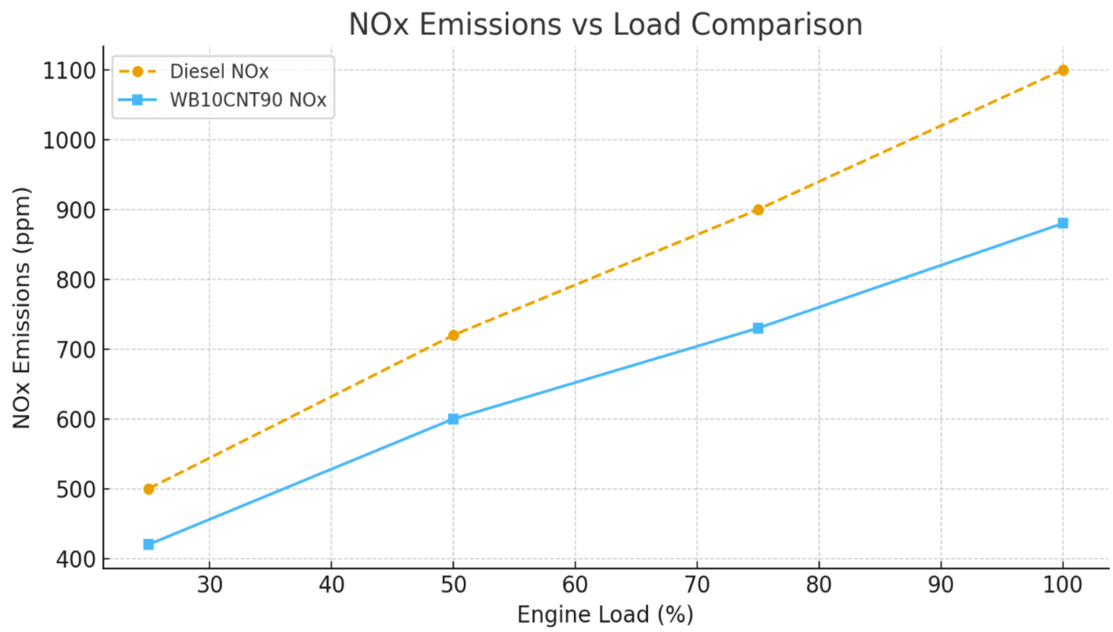

Figure 10. NOx vs. Load for Diesel and WB10CNT90

Table 6 presents a comparative analysis of economic and environmental indicators for Diesel and WB10CNT90. Although production and market prices are slightly higher for WB10CNT90, the blend demonstrates a 17% reduction in CO_2 emissions and a significantly higher sustainability index, indicating its strong potential for commercial adoption.

Table 6. Economic and Environmental Comparison of Diesel and WB10CNT90.

Fuel Type	Production Cost ($/L)	Market Price ($/L)	CO_2 Reduction (%)	Expected Market Adoption (%)	Sustainability Index (0-10)
Diesel	0.95	1.2	0	100	3
WB10CNT90	1.1	1.35	17	78	8

Table 7. Comparative Engine Performance and Emission Parameters for Diesel and WB10CNT90.

Load (%)	Diesel_BTE (%)	WB10CNT90_BTE (%)	Diesel_BSFC (g/kWh)	WB10CNT90_BSFC (g/kWh)	Diesel_NOx (ppm)	WB10CNT90_NOx (ppm)
25	18.2	20.3	420	375	500	420
50	23.4	26.2	350	305	720	600
75	26.8	30.5	280	245	900	730
100	28.9	33.1	250	210	1100	880

Table 7 summarizes key engine performance and emission characteristics for Diesel and WB10CNT90 across different load conditions. WB10CNT90 consistently shows higher BTE, lower BSFC, and reduced NO_x emissions compared to Diesel, confirming its superior combustion efficiency and environmental advantages. A new comparison table has been added, summarizing percentage improvements in BTE, BSFC, CO, HC, CO_2, and the corresponding NOx variations. Calculations follow standardized percentage change formulas to ensure transparency in table 8.

Table 8. Comparative Engine Performance and Emission Parameters for Diesel and WB10CNT90 in percentage.

Load (%)	Diesel BTE (%)	WB10CNT90 BTE (%)	BTE improvement (%)	Diesel BSFC (g/kWh)	WB10CNT90 BSFC (g/kWh)	BSFC reduction (%)	Diesel NOx (ppm)	WB10CNT90 NOx (ppm)	NOx change (%)
25	18.2	20.3	11.5	420	375	−10.7	500	420	−16.0
50	23.4	26.2	12	350	305	−12.9	720	600	−16.7
75	26.8	30.5	13.8	280	245	−12.5	900	730	−18.9
100	28.9	33.1	14.5	250	210	−16.0	1100	880	−20.0

CONCLUSION AND FUTURE SCOPES

The present study demonstrates the strong potential of the WB10CNT90 blend—comprising 10% Waste Cooking Oil Methyl Ester (WCOME), 90% conventional diesel, and 90 ppm MWCNTs—as a high-performance, environmentally conscious, and commercially viable alternative to fossil diesel. The investigation covered performance behavior, combustion efficiency, emission characteristics, dispersion methodology, and preliminary economic feasibility, offering a holistic assessment of nanotechnology-assisted biodiesel formulations. The comprehensive experimental and analytical investigation on the WB10CNT90 blend highlights the transformative potential of nanotechnology-assisted biodiesel formulations in achieving both performance enhancement and environmental sustainability. The unique thermal conductivity, catalytic reactivity, and high surface area of CNTs significantly enhanced combustion processes by improving atomization, flame propagation, and oxidation of hydrocarbons. As a result, Brake Thermal Efficiency (BTE) improved by approximately 15% across engine loads, while Brake Specific Fuel Consumption (BSFC) decreased by around 12%, demonstrating superior energy conversion and fuel savings. Emission characteristics further confirmed the advantages of CNT incorporation, with substantial reductions in CO (25%), HC (20%), and CO_2 (17%) compared to diesel. The increase in NOx emissions (8–10%) remains manageable through common mitigation strategies such as EGR and SCR, and does not diminish the broader environmental and performance benefits of the blend. From an economic and commercial perspective, WB10CNT90 shows promising scalability. While its production cost ($1.10/L) is slightly higher than diesel, the improved combustion efficiency and lower fuel consumption offset this difference over long-term operational use. The blend aligns with global sustainability goals, offering a strong business case for adoption by transportation fleets, municipal services, and industrial power applications. The sustainability index rating of 8/10 is driven by the dual advantages of waste-derived feedstock utilization and performance-driven nanotechnology integration. The drop-in compatibility of WB10CNT90 with existing engines and distribution networks further supports rapid deployment without major infrastructure modifications. Technically, the success of WB10CNT90 arises from its synergistic formulation: the oxygen-rich renewable biodiesel component enhances combustion, while

CNTs accelerate oxidation kinetics, improve thermal distribution, and promote more complete fuel utilization. The use of Carbon Nanotubes (CNTs) in fuel applications requires careful consideration of environmental and occupational safety. CNTs, especially in airborne or respirable form, can pose inhalation risks and have been associated with pulmonary inflammation and oxidative stress, as highlighted in recent nanosafety and toxicology studies. To minimize exposure, handling should be performed in controlled environments using appropriate engineering controls such as localized exhaust ventilation, sealed mixing systems, and HEPA filtration. Personal protective equipment—including N95 or P100 respirators, gloves, and lab coats—is recommended during preparation and blending. Environmentally, CNTs should be stored, transported, and disposed of according to hazardous nanomaterial guidelines to prevent accidental release into the ecosystem. Although CNTs improve combustion efficiency and reduce major emissions, further research is needed to assess the fate of CNT residues in exhaust systems and their long-term environmental impact. Implementing strict safety measures ensures that CNT-integrated fuels can be developed responsibly and sustainably. Ultrasonication ensured uniform CNT dispersion and fuel stability, both essential for reliable CI engine performance. Overall, the reduction in soot-forming emissions, improved thermal efficiency, and fuel economy establish WB10CNT90 as a robust next-generation green diesel candidate.

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