CI&CEQ
Chemical Industry & Chemical Engineering Quarterly
Available online at
Association of the Chemical Engineers of Serbia *AChE*
www.ache.org.rs/CICEQ
Chem. Ind. Chem. Eng. Q. 32 (3) 199–212 (2026) CI&CEQ

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SCIENTIFIC PAPER

UDC 662.756.3:662.7558.2:621.43

STUDY OF COMBUSTION AND PERFORMANCE IN A DIESEL ENGINE FUELED BY BIODIESEL-NANOPARTICLE BLENDS

Highlights

- Energy utilization from Avocado waste peel is extensively studied.
- GONPs nanoparticles were used as an ignition enhancer.
- AWPB+GONPs 50 ppm improved BTE by 5.98% and BSEC reduced by 30.12% compared to diesel.
- AWPB+GONPs blends, with their stable and reliable performance, are promising alternatives to diesel.

Abstract

This study examines the combustion and performance of avocado waste peel biodiesel (AWPB) combined with graphene oxide nanoplates (GONPs) as a substitute fuel for diesel engines. It also aims to assess the impact of engine combustion and performance while considering the feasibility of employing waste materials in fuel generation. The test fuels diesel, AWPB, AWPB+GONPs 50 ppm, and AWPB+GONPs 100 ppm were evaluated. The results showed that in-cylinder pressure in AWPB decreased by approximately 3.6% compared to diesel, while the heat release rate (HRR) increased notably in the AWPB+GONPs 100 ppm blend. Additionally, diesel exhibited higher ignition delay (ID) and combustion duration (CD) than all biodiesel blends. The addition of GONPs in AWPB led to a 5.98% increase in brake thermal efficiency (BTE) and a 30.12% reduction in brake-specific energy consumption (BSEC) compared to diesel. However, diesel still demonstrated higher engine torque, indicated mean effective pressure (IMEP), and air-fuel ratio (A/F ratio) relative to biodiesel fuels, whereas AWPB showed a higher exhaust gas temperature (EGT). These findings suggest that avocado peel biodiesel, when enhanced with GONPs, is a viable and cleaner alternative to conventional diesel, offering improved combustion efficiency and reduced energy consumption.

Keywords: waste to energy; avocado waste peel biodiesel; graphene oxide nanoplates; performance.

INTRODUCTION

The global fuel demand has increased due to the exhaustion of fossil fuel sources. Fossil fuels are paramount in facilitating the operation of the entire transportation system. Diesel engines substantially improved the country's energy efficiency because of their efficient fuel consumption and decreased engine exhaust emissions [1]. The presence of temporary urban differentiation and pollutants emitted at the road level presents a significant peril to the natural surroundings and has detrimental effects on human well-being [2]. Automobile research has brought attention to this highly significant issue. Consequently, a considerable amount of research is being conducted on alternative fuels, which have the potential to be derived not just from renewable sources but also yield substantial reductions in emissions. This fuel possesses the potential to not only mitigate the challenges associated with fossil fuels but also to facilitate further exploration of alternative energy resources, thereby decreasing our reliance on fossil fuels. Biodiesel, a fuel obtained from diverse sources such as vegetable oil, animal fat, and waste cooking oil, is the only feasible alternative in this context [3]. Environmental degradation and significant expansion in the usage appropriate to fossil fuels emphasize the potential usage of biodiesel as a diesel replacement [4].

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Email: nmj.mech@rmkec.ac.in
Paper received: 12 November 2024
Paper revised: 4 July 2025
Paper accepted: 1 September 2025

https://doi.org/10.2298/CICEQ241112024N

Biofuels, an environmentally friendly fuel, are increasingly recognized as a viable and promising alternative for diesel engines in current and future contexts. Biodiesel is derived from sustainable and enduring feedstocks through transesterification, characterized by the absence of aromatics or sulfur compounds [5]. In recent years, a significant study has been undertaken to employ algal oil, pine oil, lemon, and orange peel oil with enhanced diesel engine outcomes [6]. On the other hand, the oil obtained from the new peel of lemon fruits and the orange peel has received virtually little research [7]. The studied orange peel biodiesel blends in a diesel engine showed a significant 15% decrease in nitrogen oxide (NOx) emissions relative to pure diesel. This is attributed to the oxygen content in biodiesel, which improves combustion efficiency and diminishes NOx production [8]. Evaluated lemon peel biodiesel and observed a 12% decrease in carbon monoxide (CO) emissions at higher biodiesel blend ratios. The lower CO emissions indicate more complete combustion, as the oxygenated nature of biodiesel facilitates better oxidation of carbon compounds [9]. Investigated mosambi peel biodiesel blends and found a 10% reduction in NOx emissions, alongside a 20% reduction in smoke opacity. The reduced smoke levels were attributed to the biodiesel's cleaner combustion properties, which resulted in fewer soot particles [10]. Mosambi peel biodiesel increased brake-specific fuel consumption (BSFC) by 5%, reducing carbon monoxide emissions by 18% and contributing to a cleaner exhaust profile [11].

Recent advances in biodiesel research have focused on using nanoparticles to enhance performance and reduce emissions in diesel engines. Iron oxide nanoparticles in neem oil biodiesel resulted in a 25% reduction in CO emissions and improved overall engine performance by 8% [12]. Evaluated by using silicon dioxide nanoparticles with Pongamia biodiesel in a diesel engine, the results observed a 19% decrease in hydrocarbon (HC) emissions [13]. Evaluated magnesium oxide nanoparticles in rice bran biodiesel blends, which reduced NOx emissions by 12% and improved thermal efficiency by 5% [14]. Cerium oxide nanoparticles in rubber seed oil biodiesel increased thermal efficiency by 9% and reduced particulate emissions by 20% [15]. The results achieved a 10% improvement in BSFC and a 15% reduction in smoke emissions using titanium dioxide (TiO_2) nanoparticles in biodiesel derived from fish oil [16]. The diesel engine's brake thermal efficiency (BTE) was enhanced using different percentages of TiO_2 nanofluid synthesized with orange peel oil. This composition was blended with diesel fuel and found to increase BTE [17]. *Bauhinia parviflora* biodiesel (BPB), with the addition of water and di-tert-butyl peroxide (DTBP) emulsion, is utilized in diesel engines. They discovered that using a BPB and water/DTBP combination efficiently improves engine performance. Waste pork fat is effectively extracted as biofuel, mixed with GONPs, and tested by an engine. The best oxygen concentration increases engine efficiency with reduced NOx smoke. It acts as the best additive and is activated by good solubility [18].

Avocado peel is a significant agro-industrial waste byproduct generated from food processing industries, with global avocado production exceeding 8 million metric tons annually. The peel accounts for roughly 12–15% of the total fruit weight and is often discarded without valorization. Studies have shown that avocado peels contain a considerable amount of extractable oil (up to 15–18% by dry weight), making them a promising non-edible, lignocellulosic feedstock for biodiesel production. Its availability, high oil yield, and low economic value make it a sustainable candidate for second-generation biodiesel, aligning with waste-to-energy goals.

Novelty and motivation of the research

This study presents a novel and sustainable approach to biofuel production by utilizing avocado peel waste, an underutilized byproduct of the fruit processing industry, as a feedstock for biodiesel synthesis. This agro-waste valorization not only addresses waste management challenges but also contributes to circular bioeconomy practices. Additionally, the research examines the role of GONPs, a material with exceptional thermal and oxidative properties, as a performance-enhancing additive in biodiesel blends. The application of GONPs in avocado biodiesel combustion has been sparsely explored in prior literature, making this study a significant contribution to the field.

The primary objective is to evaluate the combustion and performance characteristics of AWPB and its blends with varying concentrations of GONPs in a diesel engine. Rather than aiming to surpass diesel in every metric, the study seeks to optimize thermal efficiency, reduce energy consumption, and assess the combustion behaviour of a renewable, waste-derived fuel enhanced by nanotechnology. This research ultimately aims to advance sustainable fuel alternatives that align with global efforts toward carbon neutrality, energy diversification, and the development of a circular economy.

MATERIALS AND METHODS

Avocado peel oil extraction

This work used the steam distillation method for avocado peel oil extraction, as shown in Figure 1. This plant consists of four sections. In the first section, the water is heated and converted into steam, and then the steam passes into the second section over the avocado peel. Then, steam is cooled in the third section and collected in the fourth section as a combination of water and avocado peel oil. Due to density discrepancies, the oil of avocado peel was separated from the combination. A 580 mL avocado peel oil was produced from 1 kg of avocado peel. The direct utilization of avocado peel oil in diesel operations is unsuitable due to its viscosity.

Avocado peel biodiesel production

The transesterification process, a crucial step in biodiesel production, is intricately dependent on the oil's free fatty acid (FFA) level. Since the FFA content of the extracted avocado peel oil was measured at 1.11%, which

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is below the 2% limit that necessitates acid esterification, a single-step base-catalyzed transesterification process was sufficient and appropriate. This approach ensured efficient conversion while maintaining biodiesel quality as per ASTM standards. The experimental process was meticulously executed: 100 mL of avocado peel oil was added to a 500 mL flask and heated using an oil bath. A catalyst was introduced under a 1:6 methanol-to-oil molar ratio, followed by sonication for 30 minutes to enhance reaction kinetics. The transesterification reaction used potassium hydroxide (KOH) as a catalyst at a concentration of 1 wt% of oil. Methanol (purity ≥ 99%) and KOH were produced by Chennai Chemicals, Chennai. Moreover, the reaction was carried out under continuous stirring to ensure homogeneity. A reflux condenser was used to minimize methanol loss, and the reaction was maintained at 80 °C for 90 minutes. The resulting mixture, containing methyl esters, glycerol, and catalyst residues, was centrifuged at 1,500 rpm for 10 minutes to achieve phase separation. The upper methyl ester layer was collected and further purified using a rotary evaporator to remove excess methanol. Finally, the biodiesel and glycerol layers were separated using a separating funnel. To ensure fuel quality and reproducibility, key physicochemical properties, including kinematic viscosity, density, calorific value, cetane index, and flash point, were measured and are presented in Table 1. These properties not only confirm the quality of our biodiesel but also its compliance with ASTM standards, thereby bolstering the scientific validity and repeatability of our experimental process.

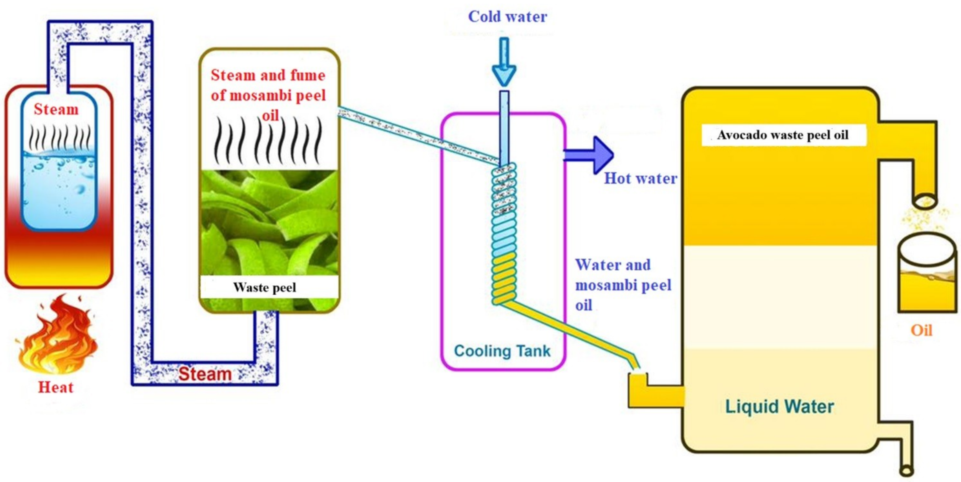

Figure 1. Schematic layout of the steam distillation method.

Nanoparticles

In this research, GONPs are selected for their role as an antioxidant that enhances the stability of Avocado peel biodiesel blends. To further improve biodiesel performance, nanoparticles are incorporated as additives. This innovative approach optimizes fuel properties such as combustion efficiency, oxidative stability, and emissions reduction. Nanoparticles are chosen based on their small size (typically 10-100 nm), which increases surface area and catalytic activity [19]. Nanoparticles offer excellent thermal stability and improve combustion by promoting more complete fuel burning, thus reducing harmful emissions [20]. Their ability to enhance oxidative stability is crucial for prolonging the storage life of biodiesel, especially in combination with GONPs, which scavenges free radicals to prevent fuel degradation. The nanoparticles are carefully dispersed using ultrasonication and mechanical stirring to ensure uniform distribution in the biodiesel blend, preventing agglomeration [21]. Nanoparticles were dispersed using an ultrasonicator operating at 40 kHz and 300 W for 30 minutes, combined with mechanical stirring at 500 rpm. The dispersion was conducted at room temperature to avoid thermal degradation of the biodiesel blend. By integrating GONPs with these nanoparticles, the research aims to significantly enhance the biodiesel's stability and overall performance, making it a sustainable and efficient alternative to conventional diesel.

GONPs are two-dimensional carbon-based nanomaterials with a high surface area and excellent thermal and oxidative properties. It appears as a white crystalline powder and is highly stable, with a melting point of 70-71 °C. GONPs work by donating hydrogen atoms to neutralize free radicals, thus halting the oxidation process in food, pharmaceuticals, and fuels. GONPs play a crucial role in preventing oxidative degradation in the context of biodiesel, a common issue due to the unsaturated fatty acids in biodiesel. GONPs improve biodiesel's shelf life and overall quality by stabilizing the fuel and reducing the formation of gums and peroxides. Typically added at concentrations between 0.01% and 0.1% by weight, GONPs ensure the biodiesel remains stable during storage and under various environmental conditions. Its effectiveness in fuel applications makes it a vital additive for improving biodiesel blends' long-term performance and stability [22].

Characterization of GONPs

GONPs used in this study were procured from Chennai Chemicals, Chennai, Tamil Nadu, India, with a reported purity of 99.9%. To verify the structural and morphological characteristics of the GONPs, two complementary analytical techniques, X-ray diffraction (XRD) and scanning electron microscopy (SEM), were employed. The XRD analysis was performed to identify the crystalline structure and phase composition of the GONPs. The XRD pattern displayed three significant peaks at 2θ angles of 31.596°, 27.038°, and 45.399°, indicating the presence of an amorphous carbon-rich phase. The broad and low-intensity nature of these peaks confirms the semi-crystalline, layered structure typical of graphene oxide, with partial disorder and oxidation. SEM was used to evaluate the surface morphology and microstructure of the GONPs. GONPs exhibited wrinkled and layered sheet-like morphology with randomly distributed ultrathin flake structures. These features confirm the large surface area and high aspect ratio, which are advantageous for improving fuel atomization and combustion when blended with biodiesel. These characterization results support the functional role of GONPs as combustion enhancers, owing to their high surface reactivity, oxidative stability, and morphological suitability for uniform dispersion in fuel. Figure 2 shows the XRD and SEM analysis of GONPs.

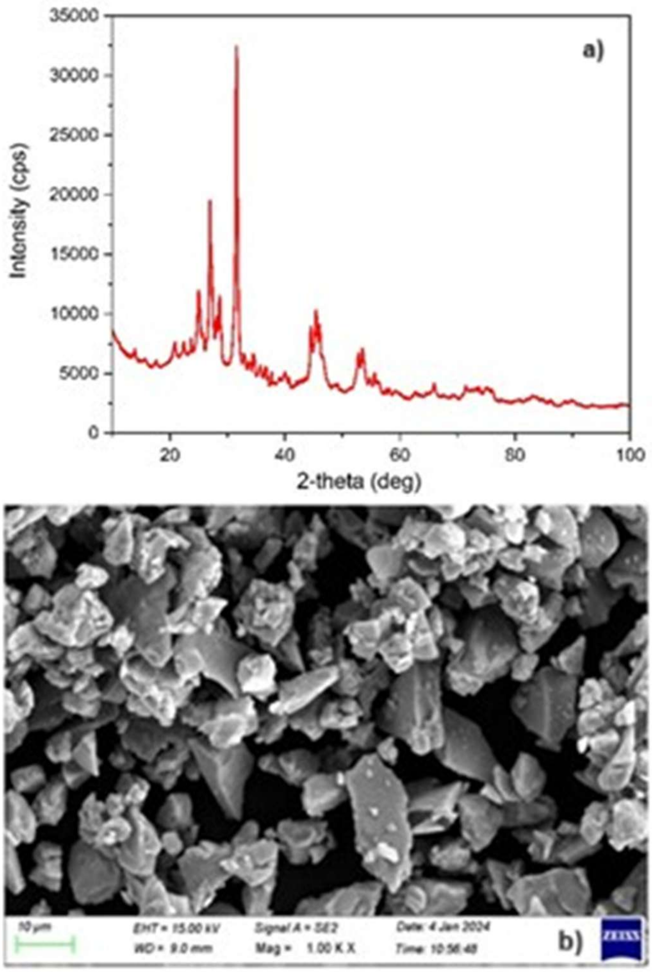

Figure 2. (a) The XRD and (b) SEM analysis of GONPs.

Preparation of test fuels

Two different biodiesel blends were prepared, incorporating GONPs nanoparticles in different ratios, such as 50 and 100 ppm. These GONPs nanoparticles play a crucial role in the blending process, as they act as stabilizers, preventing phase separation and sediment formation in the blends. The blending process is a meticulous operation initiated by a mechanical agitator to ensure thorough mixing of the components. This sets the stage for the ultrasonicator, a vital tool in the process, to further enhance the homogeneity of the mixture. The high-frequency sound waves generated by the ultrasonicator create microscopic bubbles and pressure fluctuations, which break down any immiscible components and ensure complete mixing. This method accelerates the blending process, eliminating the need to wait long periods (such as an hour) to ensure complete miscibility. The fuels are diesel, AWPB, and AWPB-GONPs blends (AWPB+GONPs 50 ppm and AWPB+GONPs 100 ppm), respectively. After blending, the fuel mixtures are left to stabilize and subjected to a 30-day long-term stability test. This comprehensive testing period ensures that all properties of the blends, such as phase separation, sediment formation, oxidative degradation, and overall compatibility, are thoroughly monitored. The results from this testing show that the biodiesel-diesel blends, including those with GONPs, exhibit no significant differences or instability, confirming that the mixtures remain stable over time and are suitable for further application and research. Table 1 shows the properties of the test fuels.

Experimental facilities and setup

In this study, the electronic fuel injection (EFI) system of a Kirloskar TV1 diesel engine was upgraded and modified with electronic sensors and transducers, all integrated via an open-type electronic control unit (ECU) using Nira i7r specifications. The system architecture was designed to optimize the control of fuel injection parameters such as pressure, timing, and delivery rate, which are crucial for improving engine performance and emission characteristics. Figure 3 (a) shows the experimental layout, and Figure 3 (b) shows the photograph of the test rig, which involved retrofitting the engine with advanced EFI components to replace the traditional mechanical system. Various tortious sensors were employed to monitor and regulate the engine's Rail pressure sensors along the fuel delivery path to measure and control the pressure in the common rail. This data was continuously fed to the ECU and processed in real-time to maintain the required fuel pressure for precise delivery. The Nira i7r ECU played a central role in managing these parameters, as it is designed to handle complex multi-variable inputs and control multiple aspects of the engine's fuel injection system with high precision. This ECU is compatible with various sensor inputs, including temperature, pressure, and flow sensors, making it ideal for high-performance diesel engine management. The fuel injection system was also modified to incorporate a high-pressure fuel pump attached to the fuel filter. This setup ensured that the injection pressure remained consistent throughout the engine's operation, which is critical for efficient fuel atomization and combustion. The common rail in this system was responsible for distributing fuel at high pressure to each injector. Under the precise control of a six-pole solenoidal valve, the injectors played a crucial role in the system. This valve provided precise control over the fuel injection timing and duration, allowing the system to sustain higher injection pressures, leading to more efficient combustion.

The fuel line modifications and the addition of the high-pressure pump and sensors were crucial in ensuring that the fuel was delivered with the appropriate pressure and timing, which the Nira i7r ECU regulated. This sophisticated control system allowed for enhanced engine performance, including improved fuel efficiency, lower emissions, and better overall combustion characteristics. The upgrade involved integrating advanced sensors, transducers, and a highly capable ECU to control fuel injection parameters accurately. This system allowed the Kirloskar TV1 engine to operate more efficiently, with better emission control and improved performance metrics.

Table 1. Physical properties of the fuel.

Characteristics	Standard	Diesel	AWPB	AWPB + GONPs 50 ppm	AWPB + GONPs 100 ppm
Kinematic viscosity, CST at 40 °C	ASTM D 445	3.1	2.6	2.595	2.4
Density (kg/m^3)	ASTM D 1298	840	790	840.8	866.6
Lower heating value (LHV) (MJ/kg)	ASTM D 240	42.51	39.26	38.29	35.78
CCI	ASTM D 976	47	51	47.7	46.4
Flashpoint (°C)	ASTM D 93	75	165	122	124

The setup demonstrated the potential for significant enhancements in diesel engine technology by adopting electronic fuel injection systems and modern control units. Test engine specifications are mentioned in Table 2. The test engine was coupled with an eddy current dynamometer to apply a controlled load. A piezoelectric pressure transducer was mounted on the cylinder head for in-cylinder pressure measurements, while a K-type thermocouple was used for exhaust gas temperature monitoring. Fuel consumption was measured using a burette and stopwatch method, and all signals were recorded via a high-speed NI data acquisition system.

Table 2. Specification of the engine.

Make and model	Kirloskar, TV1
Cylinder & Stroke	1 & 4
Bore X Stroke	87.5 x 110 mm
Swept volume	661cc
Speed	1500 rpm
Rated output	3.5 kW at 1500 rpm
CR	1:17.5
Cooling method	Water-cooled
IT, CA bTDC	23°
Injection Pressure	600 bar

EXPERIMENTAL PROCEDURE

The impact of biodiesel and biodiesel mixing with GONPs nanoparticles was tested in the diesel engine. To acquire early data, initially, the engine operated with diesel fuel and ensured stable conditions; the engine was run five minutes before each examination. The engine was tested under the brake power of 1.1, 2.2, 3.3, 4.4, and 5.5 kW at standard working conditions. The temperature range at which the lubricating oil is kept is typically between 85 and 90 °C. The test engine undergoes continuous operation for 15 minutes, during which its performance is systematically observed. After three test iterations, the accuracy numbers were merged.

To ensure the reliability and repeatability of the experimental data, each test was conducted three times under identical conditions, and the average values were used for all performance and combustion parameters. Standard deviations were calculated to assess variability. Furthermore, a one-way ANOVA test was performed to statistically validate the differences in BTE across the four test fuels. The results confirmed statistically significant differences (F = 1245.0, $p < 0.05$), indicating that the variations in BTE among Diesel, AWPB, AWPB+GONPs 50 ppm, and AWPB+GONPs 100 ppm are meaningful and not due to random error.

RESULTS AND DISCUSSIONS

The investigators observed and studied various engine attributes, encompassing combustion and performance. These specific attributes will be elaborated upon further in the following sections. By generating a graphical representation, the researchers also compare the AWPB, AWPB+GONPs 50 ppm, and AWPB+GONPs 100 ppm with the baseline diesel.

Combustion analysis

Measurement of combustion in diesel engines is significant in studying the impact of biodiesel/nanoparticle blends on standard working conditions. Combustion analysis comprises measuring the cylinder pressure and HRR concerning the crank angle (CA).

In-cylinder pressure

Fuel usage measured during the premixed ignition phase of a diesel engine is an effective indicator for evaluating combustion efficiency. The presence of CA during combustion significantly affects pressure [23]. Moreover, the assessment of the inner cylinder pressure of an engine holds significant importance as it indicates the efficiency of the air-fuel mixture during the combustion process. It significantly impacts engine brake power and exhaust emissions [24]. Figure 4(a) illustrates the cylinder pressure variances from various crank angles among test fuels. The peak in-cylinder pressure was observed to be 74.2 bar for diesel, 71.5 bar for AWPB, 72.4 bar for AWPB+GONPs 50 ppm, and 72.8 bar for AWPB+GONPs 100 ppm. The diesel fuel demonstrated a higher peak in-cylinder pressure than other test fuels. This phenomenon primarily arises due to the extended duration of the ignition delay (ID) time. This occurrence leads to enhanced air/fuel mixture homogeneity, resulting in a robust premixed combustion stage and increasing maximum cylinder pressure [25]. AWPB-GONPs blends decreased in-cylinder pressure compared to diesel fuel, which is attributable to many aspects, including combustion characteristics and fuel qualities. Biodiesel generally exhibits greater viscosity and reduced energy density than diesel, resulting in less effective atomization and air-fuel mixing. This may lead to incomplete combustion and diminished peak combustion temperatures, decreasing the total pressure produced in the combustion chamber [26].

Moreover, utilizing nanoparticle blends is frequently lower than conventional diesel fuel, attributable to nanoparticles' distinct combustion properties and behaviour [27]. Although nanoparticles are incorporated to enhance combustion efficiency and diminish emissions, they may also affect ignition characteristics and combustion dynamics in a manner that could hinder the formation of more significant pressure [28]. The nanoparticles might prolong ID, leading to a diminished combustion rate, which may decrease the peak combustion temperature and lower the in-cylinder pressure [29]. Moreover, nanoparticles may modify the fuel's viscosity and surface tension, influencing the atomization and amalgamation of the fuel-air combination. This suboptimal atomization may result in incomplete combustion, hence contributing to reduced pressure levels within the combustion chamber. Consequently, whereas nanoparticle mixes may improve specific facets of engine performance, their influence on combustion dynamics might lead to a reduction in in-cylinder pressures relative to traditional diesel [30].

Heat release rate

The HRR serves as a numerical measurement for assessing the efficacy of combustion processes. The analysis of HRR has the potential to provide a significant number of valuable insights into many aspects of cylinder head design, strategies of fuel injection, fuel properties, working conditions, and their respective influences on combustion behaviour and overall engine performance [31]. The diesel engine consists of two primary combustion stages: premixed and diffusion. The initial HRR curve segment exhibited a negative magnitude because of the evaporation of fuel commencement occurring within the ID period [32]. The HRR variations for the test fuels are shown in Figure 4(b). The maximum HRR record was 72.7 J/°CA for diesel, 74.1 J/°CA for AWPB, 76.3 J/°CA for AWPB+GONPs 50 ppm, and 80.6 J/°CA for AWPB+GONPs 100 ppm. The 20 µm GONPs blend exhibited a greater HRR than other test fuels. This can be attributed to the positive effects of the large size of the GONPs, such as facilitating a uniform mixture, enhancing fuel spray, improving atomization of fuel, promoting efficient fuel vaporization during combustion, and ultimately resulting in a superior HRR [19].

Furthermore, GONPs are a crucial factor as an additive in biodiesel combustion. It enhances the fuel's oxidation stability, promoting a more complete combustion process. This improved combustion efficiency can lead to rapid energy release, increasing the heat release rate despite the reduced cylinder pressure. The reduced pressure can be attributed to a more volatile combustion environment, where the rapid flame propagation and combustion dynamics prevent sufficient pressure accumulation time before expansion [33]. However, the use of nanoparticles is also significant. They can modify combustion properties by facilitating heterogeneous nucleation, increasing combustion rates, and accelerating heat release rates, even under conditions of reduced cylinder pressure [34]. These nanoparticles can influence the thermal characteristics of the fuel, potentially enhancing heat transmission and accelerating ignition timings, further increasing HRR. Therefore, while seemingly counterintuitive, the observed phenomenon is crucial in understanding the complex interplay among fuel content, combustion dynamics, and the thermodynamic properties of biodiesel blends in engine contexts [35].

Ignition delay

ID refers to the interval between fuel injection and the initiation of combustion within an engine. It is pivotal to engine performance, affecting the smoothness and efficiency of combustion. An extended ID in diesel engines can result in quick, uncontrolled combustion, causing knocking and increased engine stress. In contrast, a reduced delay facilitates more controlled combustion, enhancing power and efficiency. Variables such as engine temperature, pressure, and fuels influence ID, rendering its management essential for enhanced performance and reduced emissions [36]. Figure 4 (c) illustrates the variances of ID for the test fuels. The ignition delay was measured as 9.2°CA for diesel, 11.3°CA for AWPB, 10.5°CA for AWPB+GONPs 50 ppm, and 10.0°CA for AWPB+GONPs 100 ppm. The diesel has the shortest ID owing to its elevated cetane number, which enhances fuel combustion relative to biodiesel and blends with GONPs. This marginal increase in ID with the addition of GONPs is attributed to their antioxidant nature, which inhibits free radical formation during low-temperature oxidation. Additionally, the high thermal conductivity and surface activity of GONPs can alter local spray and vaporization behaviour, slightly delaying ignition initiation, especially at higher concentrations

(100 ppm), where agglomeration or uneven dispersion may occur [21]. Biodiesel has an extended ID because of its diminished cetane number, elevated viscosity, and augmented oxygen concentration, all of which impede combustion kinetics. Incorporating GONPs (an antioxidant) at 10 ppm and 20 ppm significantly prolongs the ID, as antioxidants impede oxidation reactions and diminish the fuel's reactivity. This trend corresponds with studies demonstrating that antioxidants such as GONPs inhibit ignition by averting early combustion reactions [19].

GONPs possess high thermal conductivity and excellent oxidative stability, which contribute to improved heat transfer and promote more uniform and complete combustion. Their large surface area facilitates enhanced interaction with fuel molecules, aiding in better atomization and vaporization. Upon dispersion via ultrasonication, the GONPs remain uniformly distributed within the biodiesel matrix, thereby minimizing agglomeration and ensuring consistent combustion behaviour. During combustion, GONPs act as micro-reactive sites, accelerating local oxidation reactions and reducing ignition delay through faster pre-flame reactions. This effect is particularly evident in the increased HRR observed for AWPB+GONPs 100 ppm. However, the comparatively lower BTE of the 100 ppm blend, despite the higher HRR, indicates that excessive nanoparticle content may alter combustion phasing or reduce volumetric efficiency due to slower evaporation and denser spray. This emphasizes the need for optimal GONPs concentration, aligning with prior findings that show beyond-threshold nanoparticle additions lead to reduced performance due to altered spray dynamics and inconsistent fuel-air ratios [35].

Combustion duration

The CD in an engine denotes the period required for the air-fuel mixture to fully ignite and combust within the combustion chamber, spanning from ignition to the conclusion of combustion. It directly influences engine performance, efficiency, and emissions. A reduced combustion period facilitates faster and more efficient energy conversion, enhancing power output and fuel efficiency [37]. Nonetheless, if combustion transpires too rapidly, it may result in knocking and increased engine strain. Conversely, an extended combustion period may diminish efficiency and result in more emissions. Enhancing CD is crucial for achieving power, efficiency, and engine durability equilibrium [38]. Figure 4(d) illustrates the variances of CD for the test fuels. The combustion duration increased from 23.8°CA in diesel to 25.4°CA in AWPB, 26.2°CA in AWPB+GONPs 50 ppm, and 27.0°CA in AWPB+GONPs 100 ppm. Diesel has the briefest CD owing to its elevated energy density and accelerated combustion kinetics. Biodiesel has an extended CD due to its elevated oxygen concentration and diminished calorific value, which impedes combustion [39]. The biodiesel blends containing GONPs at concentrations of 10 ppm and 20 ppm demonstrate increasingly extended CDs. GONPs, as antioxidants, suppress oxidation, decreasing the combustion rate and extending the burning duration [40]. Elevated amounts of GONPs (20 ppm) further impede the process, as antioxidants often obstruct the oxidation reactions that facilitate fuel burning. This observation is consistent with recent studies regarding the impact of antioxidants on biodiesel combustion, indicating that antioxidants can prolong CD by diminishing the fuel's reactivity [41].

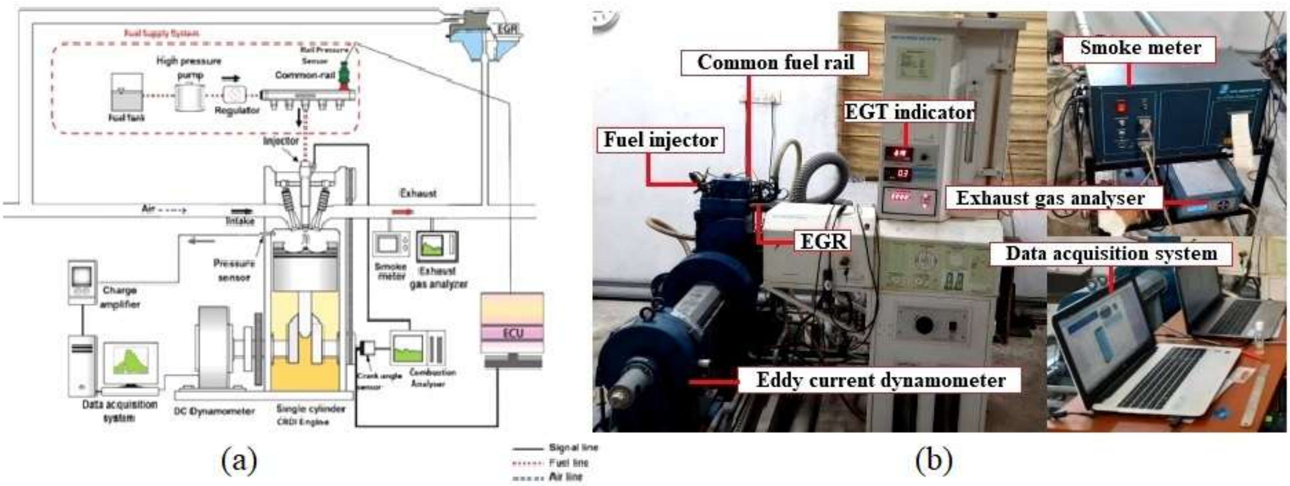

Figure 3. (a) Experimental layout and (b) photographic view of the test rig.

Performance analysis

The experimental investigation involves testing a research diesel engine powered by a blend of AWPB-GONPs under standard operating conditions. This section examines engine performance precisely regarding two key parameters: the brake-specific energy consumption (BSEC) and BTE.

Brake thermal efficiency

BTE quantifies the effectiveness of an engine in transforming the chemical energy of fuel into productive mechanical work, represented as a percentage by contrasting the brake power output with the fuel energy input. An elevated BTE signifies enhanced fuel economy, as a more significant portion of the fuel's energy is transformed into work [42]. Diesel engines generally attain superior BTE compared to gasoline engines owing to their elevated compression ratios and more effective combustion mechanisms. Elements like fuel characteristics, combustion efficiency, engine load, and technology such as turbocharging and efficient fuel injection systems substantially affect BTE. Enhancing BTE is essential for diminishing fuel consumption, augmenting engine performance, and decreasing emissions [43]. Figure 5 (a) shows the variations of BTE.

Diesel exhibits the highest BTE across all brake power levels owing to its exceptional combustion properties and energy density, enabling a more effective fuel energy transformation into work. AWPB has inferior BTE relative to diesel, principally due to biodiesel's diminished energy content and elevated viscosity, which result in heightened fuel consumption and decreased combustion efficiency [44]. The AWPB+GONPs mixtures demonstrate enhanced brake thermal efficiency compared to AWPB, with 50 and 100 ppm GONPs outperforming pure biodiesel. The antioxidant capabilities of GONPs improve fuel stability and combustion characteristics, hence alleviating certain efficiency limitations of biodiesel. The trend indicates that when BP rises, BTE is enhanced for all fuels, aligning with the anticipation that engines function more effectively under elevated loads, whereby a larger fraction of the fuel's energy is transformed into productive work [45]. The blend AWPB+GONPs 50 ppm produced 5.98% and 2.96% higher BTE than the AWPB and AWPB+GONPs 100 ppm blend at maximum brake power due to their increased fuel consumption during the premixed ignition area, and rapid combustion led to a high oxygen concentration of the GONPs [19]. GONPs exhibit exceptional thermal conductivity and surface reactivity due to their high aspect ratio and large surface area, which promote uniform heat distribution and enhance local combustion zones. Their ability to scavenge free radicals stabilizes the oxidative environment within the combustion chamber, reducing the formation of incomplete combustion byproducts [21]. Furthermore, the nanoscale size of GONPs facilitates improved atomization of the fuel blend, promoting micro-explosions that enhance droplet breakup and increase the surface area for combustion, thereby accelerating the combustion rate [26]. These effects collectively reduce ignition delay and enhance the premixed combustion phase, resulting in more efficient energy conversion. As a result, less fuel is required to produce the same output power, resulting in improved BTE [31].

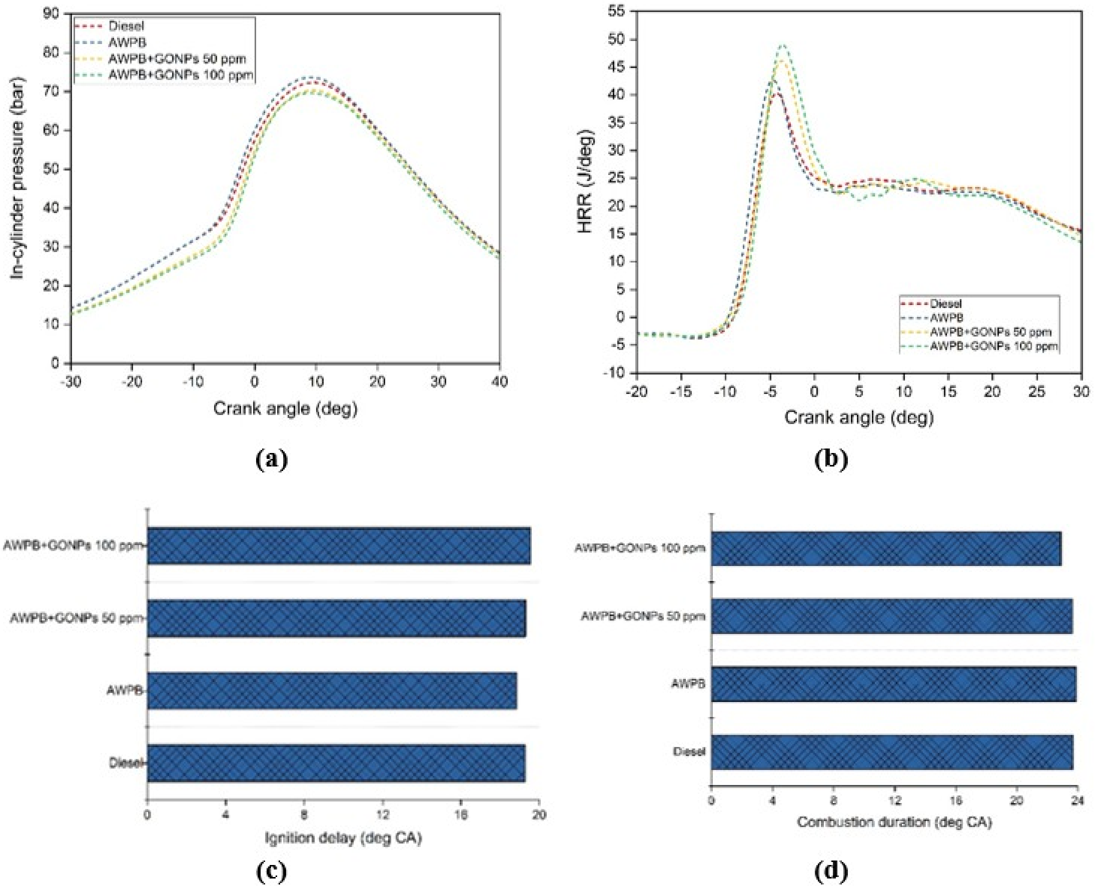

Figure 4. (a) In-cylinder pressure, (b) HRR, (c) ID, and (d) CD for the test fuels.

Brake-specific energy consumption

BSEC has combined the calorific fuel value and brake-specific fuel. There is an inverse relationship between BTE and BSFC: as one increases, the other decreases, indicating the trade-off between fuel efficiency and energy conversion efficiency in engines [46]. The outcome result and the details for the variations in BTE between biodiesel,

biodiesel-GONPs blends, and diesel also apply to BSFC [47]. Figure 5 (b) shows BSEC decreasing while increasing brake power. This is owing to the mixture's LHV compared to neat diesel fuel, which needs more fuel to achieve a given plunger movement for the injection system. BSEC increased all fuel variants relative to neat diesel. Diesel demonstrates the lowest BSEC values, indicating its superior energy density and enhanced combustion efficiency, particularly at elevated loads, where engines function nearer to ideal conditions [48]. Conversely, biodiesel exhibits consistently elevated BSEC owing to its diminished energy content and augmented oxygen content, resulting in heightened fuel consumption for equivalent power output. Biodiesel increased BSEC by 30.12% compared to diesel. The blended AWPB+GONPs 50 ppm was made with the least BSEC rather than other blends due to the addition of GONPs. GONPs' high oxygen content could hasten combustion, using less fuel to generate a similar power [19].

Engine torque

Engine torque denotes the rotational force generated by an engine's crankshaft, essential for assessing a vehicle's towing capacity and acceleration. Torque is produced when the engine's pistons move, resulting in the rotation of the crankshaft. The torque magnitude depends on engine displacement, combustion pressure, and crankshaft configuration variables. Peak torque is generally attained at reduced speed, where torque is most essential for practical driving conditions [6]. Figure 5 (c) illustrates the variances of engine torque for the test fuels. In contrast to biodiesel alone, the enhancement of engine torque noted in diesel and biodiesel-GONPs nanoparticle mixes can be ascribed to many causes elucidated in recent studies. The main reason is the improved combustion properties provided by incorporating GONPs and nanoparticles, which boost the fuel mixture's ignition quality and combustion efficiency. GONPs boost the oxidative stability of biodiesel and improve combustion characteristics by diminishing ID and increasing fuel volatility, resulting in a more complete combustion process. Integrating nanoparticles into the fuel mixture reduces the viscosity of biodiesel, enhancing atomization and spray characteristics during fuel injection. Enhanced atomization improves air-fuel mixing in the combustion chamber, leading to greater combustion efficiency and better torque output [49]. The appropriate amalgamation of biodiesel with additives such as GONPs and nanoparticles can improve performance metrics, including torque, by optimizing energy release during combustion. The synergistic effects of GONPs and nanoparticles enhance torque performance in diesel and biodiesel-GONPs nanoparticle blends relative to biodiesel alone [50].

Exhaust gas temperature

EGT denotes the temperature of the gases leaving an engine's combustion chamber via the exhaust system. It serves as a crucial metric for engine performance and combustion efficiency. Elevated EGT may indicate that the engine is under significant strain due to excessive fuel consumption or suboptimal combustion. In contrast, diminished EGT could signify incomplete combustion or reduced engine load. Monitoring EGT is essential for optimizing engine performance, as elevated temperatures can result in engine overheating and possible damage, particularly to exhaust valves, turbochargers, or catalytic converters. Conversely, sustaining appropriate EGT enhances fuel efficiency, lowers emissions, and promotes engine longevity [24]. Figure 5 (d) illustrates the variances of EGT for the test fuels. The engine EGT in diesel and biodiesel-GONPs nanoparticle blends is often lower than that of biodiesel, attributed to superior combustion efficiency and increased thermal characteristics of the fuel mixture. Incorporating GONPs in biodiesel enhances oxidation stability and combustion properties, leading to more complete fuel combustion and reduced production of unburned HC [27]. This complete combustion reduces energy loss as heat, directly contributing to decreased EGT. Integrating nanoparticles promotes superior fuel atomization, improving air-fuel mixing and combustion efficiency. Enhanced combustion dynamics facilitate a more efficient use of the fuel's energy content, resulting in reduced exhaust temperatures. The thermal features of the biodiesel-GONPs nanoparticle blend can affect EGT since the enhanced heat transfer capabilities of the blend may facilitate superior heat absorption during combustion, leading to lower EGT than biodiesel alone. The synergistic actions of GONPs and nanoparticles enhance the combustion process, reducing EGT [3]. The reduction in EGT observed with AWPB+GONPs blends is primarily due to the high thermal conductivity and oxidative stability of GONPs. These nanoparticles improve heat transfer and promote complete combustion by accelerating oxidation reactions and stabilizing the fuel against degradation. This leads to more efficient energy conversion and reduces heat loss. However, while lower EGT typically indicates better combustion, excessively low values, especially at light loads, may also suggest incomplete combustion [22].

GONPs possess high thermal conductivity, which facilitates rapid heat transfer within the combustion chamber, promoting a uniform temperature distribution and minimising localised hot spots. This enhances the combustion of fuel-air mixtures by accelerating oxidation reactions, resulting in more complete combustion [16]. Moreover, GONPs improve the oxidative stability of biodiesel blends by scavenging free radicals and reducing the likelihood of fuel degradation during storage and combustion. As a result, the fuel maintains its reactivity and ignition quality, enabling more efficient energy conversion. This improvement in combustion completeness reduces the formation of unburned hydrocarbons and decreases the amount of residual heat released into the exhaust stream, thereby lowering the EGT [31].

Indicated mean effective pressure

The IMEP is a critical metric that denotes the average pressure applied to the pistons during the combustion cycle. This metric assesses the engine's capacity to transform combustion energy into productive work derived from the pressure within the combustion chamber across a whole engine cycle. IMEP is intrinsically linked to engine torque and power output, rendering it a crucial parameter for assessing engine efficiency and performance. Figure 6 (a) illustrates the variances of IMEP for the test fuels. The observed rise in IMEP in diesel and biodiesel-GONPs nanoparticle mixes, relative to biodiesel, can be ascribed to the improved combustion efficiency and power production stemming from the distinctive characteristics of the blend. Incorporating GONPs as an antioxidant in biodiesel enhances the fuel's oxidation stability and volatility, resulting in lessened IDs and more thorough combustion. This enhancement enables elevated combustion pressures throughout the power stroke, augmenting IMEP [39]. Integrating nanoparticles into the biodiesel-GONPs mixture improves fuel atomization and spray properties by decreasing viscosity and facilitating superior air mixing. An enhanced air-fuel mixture yields more efficient combustion, resulting in elevated peak pressures within the cylinder and increased IMEP. The combined effects of GONPs and nanoparticles in biodiesel substantially enhance engine performance, as evidenced by the elevated IMEP relative to biodiesel alone [5].

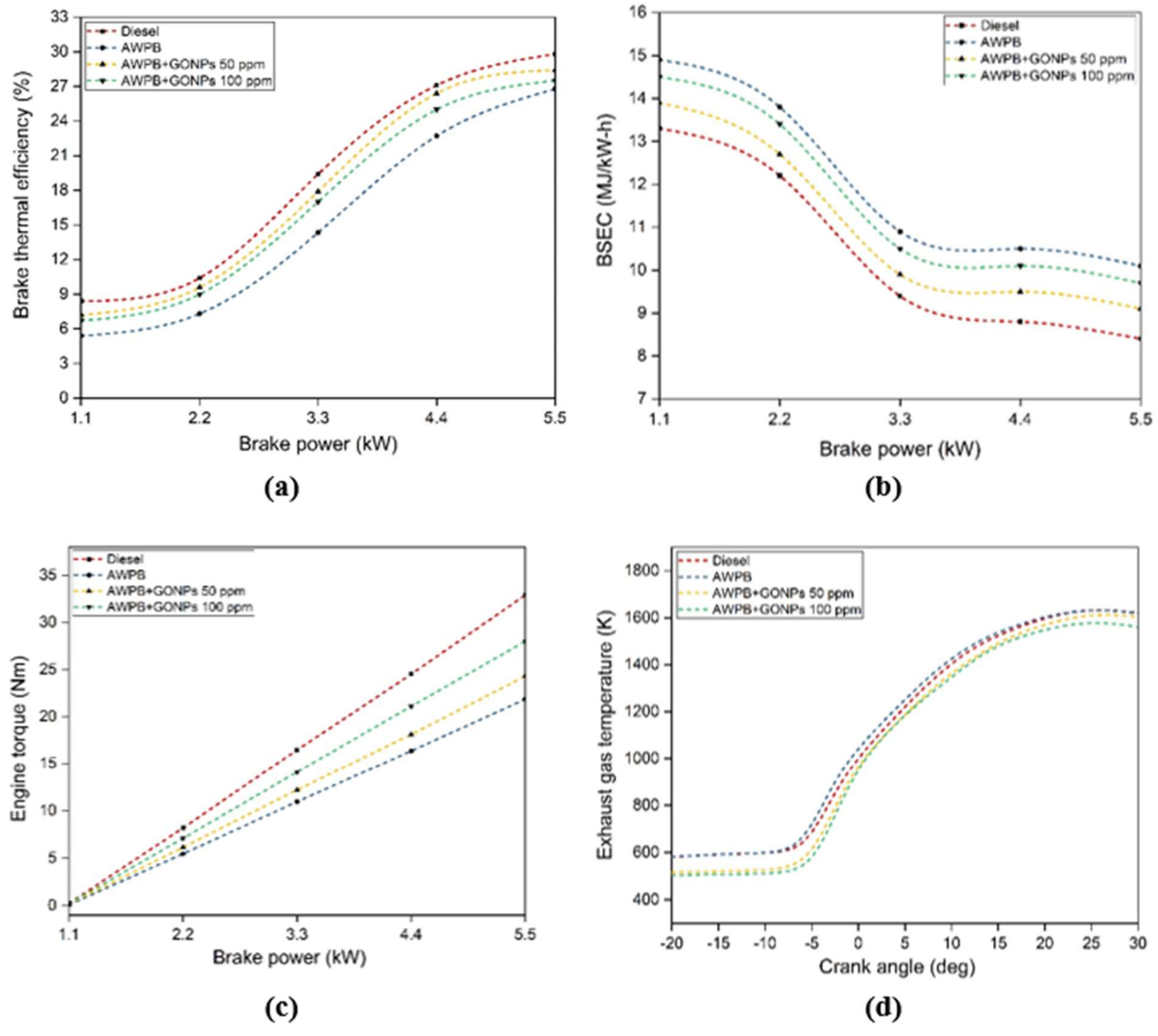

Figure 5. (a) BTE, (b) BSEC, (c) engine torque, and (d) EGT for the test fuels.

Air-fuel ratio

An engine's A/F ratio is the air-to-fuel (A/F) ratio combined and ignited in its cylinders. Assessing engine efficiency, performance, and emissions requires it. The ideal A/F ratio for gasoline engines is 14.7:1, or 14.7 parts air to 1 part fuel. The combustion process produces power, fuel economy, and low pollutants most efficiently at this ratio. A "rich" mixture has more fuel than air, increasing engine output, fuel consumption, and pollutants. A "lean" mixture has more air than gasoline, improving fuel efficiency and lowering pollutants, but it may also raise engine temperatures and cause engine knock. Proper A/F ratios improve engine durability, efficiency, and environmental compliance [23]. Figure 6 (b) illustrates the variances of the A/F ratio for the test fuels. The A/F ratio in diesel and biodiesel-GONPs nanoparticle blends is more optimal than in biodiesel alone, owing to the enhanced combustion characteristics provided by the additives. GONPs improve biodiesel's oxidative stability and volatility, facilitating superior atomization and a more consistent fuel distribution throughout the combustion chamber.

This enhanced atomization results in more efficient air mixing, improving the A/F ratio and facilitating complete combustion [51]. Furthermore, including nanoparticles in the biodiesel-GONPs blend further diminishes the fuel's viscosity, promoting finer spray patterns during injection and improving the overall quality of the air-fuel mixture. A more uniform air-fuel mixture facilitates more efficient combustion processes, yielding an optimal A/F ratio that enhances engine performance and reduces emissions. Thus, the combined actions of GONPs and nanoparticles in biodiesel yield a more advantageous A/F ratio than biodiesel alone, improving engine efficiency and performance [12].

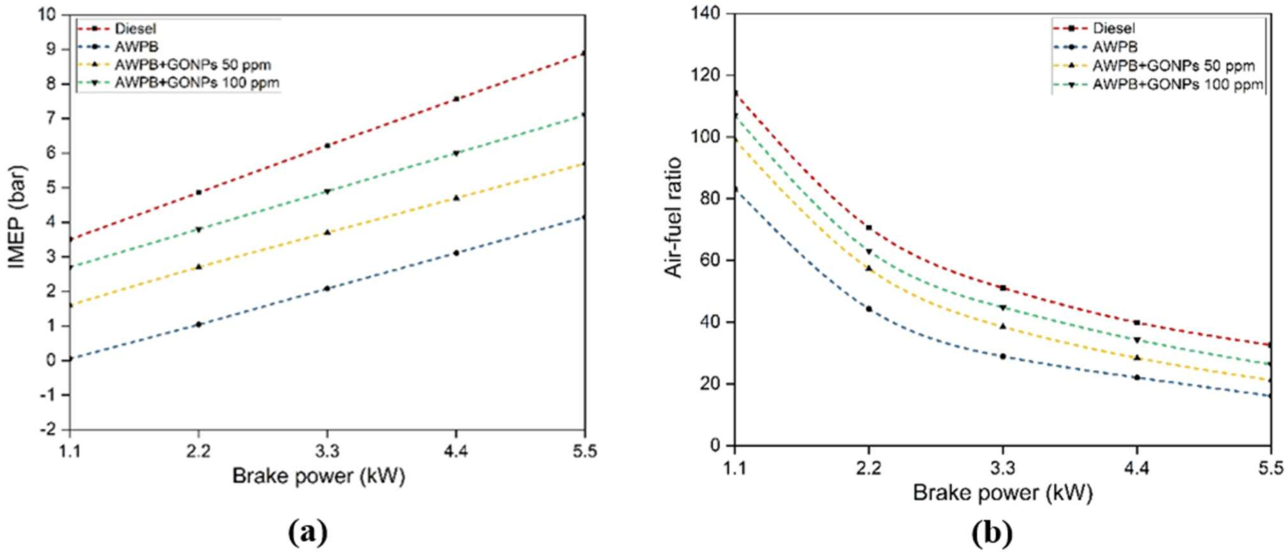

Figure 6. (a) IMEP, and (b) A/F ratio for the test fuels.

AWPB+GONPs blends exhibited an improvement in BTE and a reduction in BSEC. These enhancements were observed alongside relatively lower engine torque, indicating a mean adequate pressure and volumetric efficiency compared to diesel. This performance divergence is attributed to the inherently lower energy density and slightly higher viscosity of biodiesel, which adversely affect air-fuel mixing and combustion pressure development. Despite the oxidative and catalytic benefits provided by GONPs, these blends experience reduced torque output due to incomplete utilization of the lower heating value. Additionally, volumetric efficiency tends to decrease because biodiesel combustion increases the residual gas content and intake temperature, thereby affecting the fresh charge density.

CONCLUSION

This investigation describes the utilization of biodiesel produced from avocado fruit peel waste using the transesterification method to fuel diesel engines by adding GONPs as an ignition enhancer.

- The in-cylinder pressure increased in AWPB, and HRR increased in AWPB+GONPs 100 ppm blend compared to diesel, but the diesel fuel has a higher ID and CD than other test fuels.
- Biodiesel increased BSEC by 30.12% compared to diesel. The blended AWPB+GONPs 50 ppm was made with the least BSEC rather than other blends.
- The BTE increased in AWPB+GONPs 50 ppm blends by 5.98% and 2.96% compared to AWPB and AWPB+GONPs 100 ppm blends, but lowered by 4.92% compared to neat diesel at maximum brake power.
- Furthermore, diesel fuel has a higher engine torque, IMEP, A/F ratio, and volumetric efficiency than other test fuels, but AWPB has higher EGT than diesel.

This work concludes that adding GONPs to a biodiesel blend enhances performance, and this combination of blends is suitable for diesel engine operations.

Practical and economic considerations. Avocado waste peel offers a promising, low-cost, abundant feedstock, particularly in fruit-processing regions. Its collection, drying, and oil extraction processes must be optimized for industrial-scale implementation. Furthermore, although GONPs offer substantial benefits in improving combustion and oxidative stability, their current production cost remains a constraint for widespread commercial use. However, recent advances in green synthesis methods and waste-derived graphene oxide production pathways suggest the potential for cost reduction. We acknowledge that a detailed techno-economic assessment is necessary to validate the long-term viability of this biodiesel-nanoparticle system. Hence, we have stated this as a key direction for future work. This addition reinforces the need to balance performance advantages with economic practicality, supporting a more holistic evaluation of the fuel blend's sustainability.

Future research direction. Integrating hydrogen and bioethanol fuel injection as a dual fuel system in diesel engines can enhance performance and diminish greenhouse gas emissions, particularly with AWPB-diesel mixtures. The impact of various fuel injection techniques can be assessed to analyze a diesel engine's performance efficiency and environmental emissions, utilizing test fuels such as AWPB and diesel fuel.

NOMENCLATURE

GONPs Graphene oxide nanoplates
AWPB Avocado waste peel biodiesel
HRR Heat release rate
NOx Nitrogen oxide
CO Carbon monoxide
BSFC Brake-specific fuel consumption
BTE Brake thermal efficiency
HC Hydrocarbon
OB20L5 Orange peel oil biodiesel 20+L-ascorbic acid 5 % by volume
OB20L10 Orange peel oil biodiesel 20+L-ascorbic acid 10 % by volume
BPB Bauhinia parviflora biodiesel
DTBP Di-tert-butyl peroxide
FFA Free fatty acid
ppm part per million
LHV Lower heating value
CCI Calculated cetane index
EFI Electronic fuel injection
ECU Electronic control unit
BSEC Brake-specific energy consumption

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NAUČNI RAD

ISTRAŽIVANJE SAGOREVANJA I PERFORMANSI DIZEL MOTORA NAPAJANOG MEŠAVINAMA BIODIZELA I NANOČESTICA

Ovaj rad istražuje sagorevanje i performanse biodizela od otpadne kore avokada (AWPB) pomešanog sa nanopločama grafen-oksida (GONP) kao potencijalnog alternativnog goriva za dizel motore. Takođe, rad ima za cilj da proceni uticaj sagorevanja i performansi motora, uz razmatranje izvodljivosti korišćenja otpadnih materijala u proizvodnji goriva. Procenjena su sledeća goriva: dizel, AWPB, AWPB+GONP 50 ppm i AWPB+GONP 100 ppm. Rezultati su pokazali da je pritisak u cilindru u AWPB smanjen za približno 3,6% u poređenju sa dizelom, dok je brzina oslobađanja toplote značajno porasla u mešavini AWPB+GONP 100 ppm. Pored toga, dizel je pokazao veće kašnjenje paljenja i trajanje sagorevanja od svih mešavina biodizela. Dodavanje GONP-ova u AWPB dovelo je do povećanja termičke efikasnosti kočnice za 5,98% i smanjenja potrošnje energije specifične za kočenje za 30,12% u poređenju sa dizelom. Međutim, dizel je i dalje pokazao veći obrtni moment motora, indicirani srednji efektivni pritisak i odnos vazduh-gorivo (A/F odnos) u odnosu na biodizel goriva, dok je AWPB pokazao višu temperaturu izduvnih gasova. Ovi nalazi ukazuju na to da je biodizel od kore avokada, kada je poboljšan GONP-ovima, održiva i čistija alternativa konvencionalnom dizelu, nudeći poboljšanu efikasnost sagorevanja i smanjenu potrošnju energije.

Ključne reči: otpad u energiju, biodizel, kora avokada, nanoploče grafen-oksida; performanse.