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Performance and Emission Characteristics Evaluation of Graphene Nanoplatelets (GNP) Additives-Based Soybean and Diesel Fuel for a Compression Ignition Engine Under Varying Loads

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Abstract

The growing concern over the scarcity of fossil fuels and global warming has led researchers to explore alternative fuel sources for automobiles. In this study, different blends of soybean biofuels (B20, B30, and B40) and diesel were prepared with and without the addition of graphene nanoplatelet nanoparticles (GNPs). The GNPs were added in weights of 50, 75, and 100 ppm to the soybean oil and diesel blends, resulting in B20GNP50, B20GNP75, B20GNP100, and similar blends for B30 and B40. The performance test was conducted on a compression ignition diesel engine at 1500 rpm, 18:1 compression ratio, and loads of 25%, 50%, 75%, and 100% for both the soybean oil and diesel blends with and without GNP. The highest brake thermal efficiency (43.27% and 27.49%) is achieved for the D100GNP75 and B20GNP75 blends at full load, while the lowest brake-specific fuel consumption is observed for the B20GNP75 and D100GNP100 blends at 50% and 75% loads, compared to pure diesel. An AVL gas analyzer demonstrated that biodiesel blends have lower emissions than pure diesel. The improved engine performance and reduced emissions were attributed to the combined action of oxygen at higher temperatures in the combustion chamber and the thermal characteristics of GNP.

Keywords: Compression ignition engine; Blend; Soybean; Graphene nanoplatelets; Break thermal efficiency; Brake specific fuel consumption; Emissions.

Research Article

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1. Introduction

The transportation sector heavily influences the modern global economy in terms of fuel economy, conversion efficiency, fuel availability, and cost, all impacting the transportation industry [1]. The CI engine has rapidly pounced on its benefits since its inception in the late nineteenth century and retained its position as a top engine choice due to its higher performance, better fuel economy, and lower maintenance needs. Diesel engines are used in various contemporary transportation fleets, such as farm equipment, heavy-duty industrial machinery, power generators, passenger cars, and public transportation. Despite having many positive attributes, diesel engine exhaust is considered a significant source of air pollution and presents a substantial cancer risk to people [2]. Common air pollutants like soot, nitrogen oxides, and carbon dioxide emissions have negatively impacted the environment and human health. Researchers have suggested several methods to address these problems, including employing hybrid fuels and adding gasoline additives, which may improve engine performance and reduce exhaust emissions. Recent advancements in research have shown that nanoparticles can be innovative fossil fuel additive to boost engine efficiency and emissions characteristics in the context of strict worldwide emissions laws. Several researchers are still working on the optimal solution for the augmentation of engine performance and the degradation of emissions contents of the diesel engine, which are discussed in further paragraphs [3].

The study aims to improve the performance and quality of biodiesel made from mahua oil by adding TiO2 nanoparticles, blending a biodiesel mix of 80% diesel and 20% mahua biodiesel and 200 mg/l of TiO2. Results showed that CO emissions were 37.42%, HC emissions by 22.54%, and NOx was reduced by 4% for the biodiesel [1]. To find a more sustainable and ecofriendly fuel, researchers have looked into mahua oil; in this study, 20% mahua biodiesel with different amounts of CeO2 and Al2O3 nanoparticles mixture in a single-cylinder CI engine, running at 1500 rpm. The nanoparticles, an ultrasonic bath, and a stabilizing agent were added to keep the mixture stable. Results were a 3.25% reduction in BSFC, a 1.39% increase in brake thermal efficiency (BTE), a significant reduction in 30.73% hydrocarbon (HC), 1.27% in nitrogen oxide (NOx), and 44.13% in carbon mono-oxide (CO) [2]. This study investigated the effects of adding Al2O3 to a blend of 30% jatropha biodiesel (JB) and 70% diesel with 50 ppm of Al2O3. Experiments were conducted on a 4-stroke single-cylinder diesel engine running at 1350 rpm. The experiment outcomes reveals that BSFC increased by 3.77% for the blend JB30 and 3.82% for the Al2O3 nanoparticles. Adding nanoparticles also reduced the rate of rising combustion pressure, leading to less combustion noise [3]. CuO2 nanoparticles at 50 and 100 ppm were added to pure palm bio-diesel. The mentioned nanoparticles were added to the palm biodiesel BSFC consumption by 0.6% and exhaust gas temperature by 1.2% under peak load conditions. When 100 ppm of CuO2 nanoparticles were added, BTE improved by 0.6% at full load [4]. Using waste Avocado biodiesel mixed with manganese dropped Al2O3 nanoparticles. The blend includes 20% biodiesel mixed with diesel and 30, 60, and 90 ppm nanoparticles. All tests were conducted with the engine running at its 4.5 kW power. The results showed that adding 90 ppm of nanoparticles to the B20 led to a 5.7% increase in BSFC and a 12.1% reduction in BSFC. Emissions were also reduced by CO by 8.5%, UHC by 23.2%, NOx by 6.5%, and smoke by 20.5%, respectively [5]. Biodiesel is made from spirulina microalgae by adding a small amount of Al2O3. A diesel engine was tested at 25%, 50%, 75%, and 100% load. The fuel blends were B0, B15(15% spirulina biodiesel+85% diesel), B15N (15% spirulina biodiesel + 85% diesel + 75 ppm Al2O3), B30 (30% spirulina biodiesel + 70% diesel), B30N (30% spirulina biodiesel + 70% diesel + 75 ppm of Al2O3). For all blends, 75 ppm of Al2O3 nanoparticles were mixed, and results showed that B15 blend with B15N reduced harmful gases; B15N and B30N had higher BTE than B15 and B30 without nanoparticles [6]. This study uses test fuel to evaluate the thermal and environmental performance of a 10 kW, four-stroke, single-cylinder diesel engine, including a blend of water, diesel, and biodiesel with CeO2 nanoparticles and a smaller blend without nanoparticles. These fuels were prepared using an emulsification technique. They were mixing water and CeO2 nanoparticles into a diesel biodiesel blend. The engine was tested at various loads, 0%, 20%, 40%, 60%, 80% and 100% at constant compression ratio. The results showed that adding water and CeO2 nanoparticles to B20 fuel improved the engine BTE by 7.65% compared to diesel. The CNWED8 blend also reduced heat losses at 80% engine load. The engine running on CNWED8 emitted 12.82% reduced CO, 14.46% by HC, and 14.20% reduced NOx compared to WED8 and 30.77% by CO, 43.67%reduced HC, and 26.80% by NOx compared to diesel [7]. This research focuses on using cooking oil biodiesel mixed with nanoparticles in a diesel engine, with nanoparticles in a diesel engine with added hydrogen during testing. The fuel blends were D100 pure diesel, B10 (90% diesel + 10% biodiesel), B20 (80% diesel + 20% biodiesel), D100T10 (pure diesel with 100 ppm nanoparticles), B10T10 (90% diesel + 10% biodiesel with 100 ppm nanoparticles + 5 l/min of hydrogen), B20T10 (80% diesel + 20% biodiesel with 100 ppm of nanoparticles +5 l/min of hydrogen). Hydrogen was supplied at a constant rate of 10 l/min during the tests conducted at different engine speeds from 1800 rpm to 2800 rpm. The results showed that adding nanoparticles and hydrogen improved engine performance, BTE increased, and BSFC decreased. CO, CO2 and UHC emissions were reduced, and NOx emissions increased slightly [8]. This study focused on creating and testing nanofluids (NFs) using Al2O3 in a dual-fuel engine. First, nanofluids were prepared by mixing Al2O3 nanoparticles with diary scum oil methyl ester in concentrations of 10, 20, and 30 ppm using a conventional homogenizer and an ultrasonicator. The impact of Al2O3 nanoparticles on ignition and emissions of a single-cylinder, four-stroke, direct injection diesel engine running on a dual fuel mode with dairy scum oil methyl ester (DiSOME). and produced gas was examined. The engine tests show that using Al2O3 nanofluid and PG together results in an 11.5% increase in BSFC, 23.2% smoke, and 18.2%-21.4% in HC and CO emissions [9]. This study examines how adding a few-layered graphene and graphite nanoparticles to waste cooking oil biodiesel affects combustion and engine emissions adding graphene and graphite nanoparticles led to a 0.5-2.5% increase in peak cylinder pressure and a 1-4% decrease in the heat release rate at full load. Also, NOx emissions were reduced by 0.7-5% compared to 100% for diesel [10]. Further study was conducted on mixing a biodiesel blend from Cinphyllum (CIB20) with titanium dioxide nanoparticles in different concentrations. The fuel properties of diesel, CIB20, and CIB20 with various amounts of nanoparticles were measured according to ASTM standards. Various tests were conducted on a diesel engine using fuel blends. The results showed that the CIB20TNP80 blends did an 11% increase in BTE, BSFC decreased by 16%, and CO, HC, and smoke emissions were reduced by 30%, 21%, and 17.6%, respectively [11]. The study examined how adding Al2O3 to diesel biodiesel blends and varying engine speed affects the performance and emissions of a six-cylinder, four-stroke diesel engine. Al2O3 was added to the fuel at 40, 80, 120, and 160 ppm concentrations. The engine was tested at different speeds (800 to 1000 rpm). Using the response surface method, the study was conducted to analyze the impact of these variables on engine performance. The highest break power of 42.82 kW and torque of 402.8 Nm were achieved with 160 ppm nanoparticles concentration at 1000 rpm, and the lowest BSFC was 207.21 g/kWh. CO and HC were reduced to 1.15% and 9%, respectively. The highest CO and NOx emissions were 11.76% and 1899 ppm, respectively, at 160 ppm nanoparticle concentration and 1000 rpm [12]. The study focuses on the combustion of rice bran oil methyl ester blends with diesel magnalium nanoparticles with a concentration of 25, 50, and 75 ppm to blends of 20%, 40%, and 60% rice bran oil biodiesel. The resulting B20 blend with 25 ppm nanoparticles was a promising fuel option, and the B20 blend with 75 ppm showed good fuel potential with reduced combustion risk [13]. The researcher examines nahar oil biodiesel with and without carbon nanotube (CNT) nanoparticles in concentrations of 100 ppm and 200 ppm due to its high surface energy and a large surface-to-volume ratio, which enhances combustion and reduces emissions compared to conventional fuels. NOx was also reduced due to the catalytic activity of CNT nanoparticles [14]. The work examined the performance and emissions characteristics of watermelon oil biodiesel with and without Al2O3 nanoparticles to improve combustion, and the blends tested were B10, B20, B30, and 20 ppm additions of Al2O3. The results were conducted across various engine load conditions and decreased emissions as the biodiesel concentration increased [15]. The author conducted the experimental study to enhance the performance of diesel engines using an Oil biodiesel blend with chromium oxide nanoparticles and a dispersant at concentrations of 50, 75, and 100 ppm at various loads. The result shows an 18.66% improved cylinder pressure, 11.61% increase in heat release rate, 3.62% increase in BTE, and 3.53% decrease in BSFC, while a 14.05% reduction in CO, 12.93% for UHC, 6.66% for NOx and 22.4% for smoke compared to diesel [16]. Non-edible oils like Egyptian jatropha were explored as alternative fuels with diesel in various ratios with different concentrations of biodiesel at 75% engine load. The study's outcome reveals a 27% decrease in break power, a 9% decrease in volumetric efficiency, a 33% decrease in thermal efficiency, and 47% reduced NOx emissions and 22% smoke [17]. This study investigated how various blends were prepared by adding 15 to 75 ppm of ceria nanoparticles to B20 at an engine operating at a fixed compression ratio of 20.1 and constant speed. The output of the work shows a reduced 3.3% BSFC, and the addition of ceria dosage reduced CO and HC emissions [18]. Another work was carried out on CeO2 nanoparticles to examine the performance of diesel engines and shows the improved performance by decreasing BSFC among the sizes of the nanoparticles test 30nm nanoparticles, achieving a reduction in BSFC by 2.5%, NOx emissions by 15.7% and smoke opacity by 34.7% compared to B20 without additives [19]. This study investigates the extracted biodiesel from chlorella vulgaris. A B25 blend with additives in varying amounts was tested, and results show that B25 with 15 ml additives improved BTE and reduced BSFC compared to diesel [20]. Researchers assess the impact of adding 50 mg/l graphene nanoparticles on jatropha J20 and karanja K20 biodiesel blends and show enhancement in BTE by 4.77% and 7.17%, respectively. Smoke was reduced by 43% for both blends and NOx emissions by 8% and 14% compared to J20 and K20, respectively [21]. The investigation was carried out on the graphene nanoplatelets and 10% v/v dimethyl carbonate as fuel additives in a 30% biodiesel and 70% diesel blend. A diesel engine operating at a constant speed of 1500 rpm was employed for the experiment. It was found that the heat release rate increased by 15.45% and 9.63%, respectively, for the B30GNP60, DMC10, and BTE increased by 8.98%, and BSFC consumption increased by 25.54%.CO was reduced by 22.8% and 25.67%, respectively, NOx by 9.57%, and smoke by 12.4%, respectively [22]. The influence of alumina nanoparticles on a ternary fuel (TF) blend in a single-cylinder diesel engine adding 20 ppm alumina TF20 improved engine performance by reducing BSFC by 4.93% and increasing BTE by 7.8%. HC, CO, NOx, and smoke emissions decreased by 5.69%, 11.24%, 9.39%, and 6.48%, respectively [23]. In a recent study, an ethanol diesel blend (E5-15) with nickel zinc iron oxide nanoparticles was added and prepared using a magnetic stirrer and ultrasonicator. Moreover, adding nanoparticles increases fuel consumption and reduces BTE. Adding nanoparticles to E10 slightly increased the torque and power [24]. This study investigated the effect of adding zinc oxide nanoparticles to a diesel biodiesel ethanol blend. Engine tests showed 25 ppm of zinc oxide increased fuel consumption and reduced emissions of NOx and smoke compared to diesel [25]. The study found that blending with Alumina nanoparticles and ethanol created a stable suspension and altered fuel properties compared to diesel. This blend resulted in a higher combustion pressure and heat release rate. Additionally, the oxygen content in the biodiesel and nanoparticle mixing reduced CO and UHC emissions [26]. Jaikumar et al. [33] studied the impact of dispersant-added nanofuel on direct injection compression ignition engines using a diesel-biodiesel combination. They found that chromium oxide nanoparticles significantly improved combustion parameters, cylinder pressure, and net heat release rate compared to diesel-biodiesel blends. Additionally, alumina nanoparticles increased efficacy and reduced pollutants. Ghanbari et al. [34] found that adding alumina nanoparticles to diesel-biodiesel blends increased efficacy and reduced pollutants. The highest values of brake power and torque were achieved at 1000 rpm and 160 ppm of nanoparticle concentration. Rastogi et al. [35] investigated the influence of copper oxide nanoparticles on the operating and pollution parameters of CI engines powered by Simmondsia Chinensis biodiesel. CuO nanoparticles in various concentrations were blended into the JB20 fuel, resulting in higher BTE and reduced engine smoke, CO, and hydrocarbon emissions. Gad et al. [36] tested jatropha seeds blended biodiesel performance and combustion parameters. Screw press extraction was chosen due to its higher oil yield and improved properties. The study found that biodiesel blends were lower than crude diesel. Prabu et al. [37] conducted an experimental study on the emission reduction approach of incorporating alumina and cerium oxide nanoparticles into biodiesel. The study found that the addition of nanoparticles significantly improved brake thermal efficiency and reduced nitric oxide, carbon monoxide, unburned hydrocarbon, and smoke emissions. Syed et al. [38] also investigated the effects of nanoparticles mixed in waste cooking oil (WCO) biodiesel on the thermal performance characteristics of a VCR engine. Selvan et al. [39] conducted an experiment to determine the performance, combustion, and emission characteristics of a variable compression ratio engine with Cerium Oxide Nanoparticles and Carbon Nanotubes as fuel-borne nanoparticle additions in Diesterol (diesel-biodiesel-ethanol) mixes. Agbulut et al. [40] investigated the effects of mixes of waste cooking oil methyl ester and different metal-oxide nanoparticles on a single-cylinder diesel engine's emission, combustion, performance, vibration, and noise characteristics. The study concluded that incorporating metal-oxide-based nanoparticles into biodiesel blends can produce better results than using biodiesel alone in diesel engines.

Table 1. Details the reported studies based on emissions and performance-based results.

Ref	Nanoparticle/ Additiuve/ base fuel	Conc. (ppm)	BSFC (%)	BTE (%)	CO (%)	HC (%)	NO (%)	Smoke(%)
[27]	Titanium dioxide(TiO_2)	150 mg/l	3.25	18.42	-	38.1	-	20.1
[28]	ZnO/waste Cookong oil	90.9	30.75	13.92	0.05	34.68	71.28	-
[28]	100 ppm Zno/10%SB conc,20% water conc.	100	41.62	13.74	25.1	11.51	-	3.91
[29]	Nickel oxide/Neem biodiese blend of 25%	25 and 50	24.61	17.1	1.6	22.41	5.11	-
[30]	Al2O3/Methyl Ester of jatropha	30	35.21	-	0.081	-	20.1	-
[31]	Carbon nanotubes/ Neembiodiesel	500 and 100	20.31	14.21	5.91	6.71	9.21	7.81
[32]	CeO_2/ neat palm oil methylester	12,20 and 30	20	10.1	3.61	4.21	3.81	6.41

Table 1 shows the few reported studies based on emissions and performance-based results. Furthermore, researchers have conducted numerous studies on biofuels mixed with nanoparticles to evaluate CI engines' performance and emission characteristics. Additives can potentially reduce the harmful gases emitted from the CI engine, and nanoparticles are currently being used as additives[41][42]. A significant research gap has been identified in the literature on biodiesel fuels due to their numerous disadvantages. Biodiesel can be used as a substitute for pure diesel, but the percentage of biodiesel as a substitute is low. Further study is needed to understand the impacts of higher nanoparticle concentrations on emissions and performance. Additionally, research on graphene nanoplatelet (GNP) in biodiesel is needed to improve thermophysical characteristics, viscosity, density, cetane number, net energy content, BTE, and BSFC. There is also a lack of research on mathematical modeling and analysis of GNP blend biodiesel. In addition, researchers have studied the effects of using aluminum, iron, cerium, and titanium as additives in biofuel to reduce emissions, but very little research has been conducted on graphene nanoplatelets. This study aims to experimentally examine the performance and emission characteristics of a CI engine using soybean biodiesel, and pure diesel. This will be done with and without the mixing of graphene nanoplatelets for variable load conditions at a constant compression ratio. The obtained results will be compared with pure diesel, and the present results will be validated with reported studies.

2. Materials and Method

2.1 Biodiesel blend preparation and its properties

a) Soybean biodiesel preparation

An analytical grade of soybean oil was used in this study. The fatty acid composition was determined in a 500 ml round bottle flask. The oil was heated to 55ºC before starting the reaction. At this point, KOH solution was added to the oil under mechanical stirring at about 350 rpm, and a transesterification reaction was used to produce methyl ester. The reaction time is 1 hour. The biodiesel purification of the methyl ester was achieved by washing it with distilled water.

b) Graphene Nanoplatelets mixed biodiesel blend preparation

This study utilized graphene nanoplatelets (GNPs) as nanoparticles blended with soybean biodiesel in concentrations of 50%, 75%, and 100%. The dispersion of GNPs in the fuel was achieved through ultrasonication and stirring processes using an ultrasonicator and a magnetic stirrer (see Fig. 1(a)) apparatus for 45 minutes and 30 minutes, respectively. This was done to ensure the dispersion of GNPs in biodiesel and to prepare a homogeneous mixture of biodiesel and diesel blends (B20, B30, and B40, D100 (see Fig. 1(b)). The prepared test fuel was subjected to stability testing by being kept in a 100 ml graduated scale glass test tube under static conditions for 12 hours. The diesel and soybean biodiesel's physicochemical properties and GNP blends are tested as per ASTM standards and tabulated in Table 2. The tested blends include B20, B20GNP50, B20GNP75, and B20GNP100, and similarly with D100, B30, and B40 representing the volume percentages of soybean in diesel, and GNP representing graphene Nanoplatelets at 50, 75, and 100 parts per million (ppm) weight percent in biodiesel and pure diesel.

(a)


(b)

Figure 1. (a) Magnetic stirrer (b) Different Blends (B20, B30, and B40 with GNPs) and D100

3. Experimental setup and procedure

In this study, a single-cylinder, four-stroke diesel engine is utilized to assess its performance and emission characteristics (engine details are provided in Table 3). The diesel engine is connected to an electric loading device and an engine-type thermocouple for measuring the exhaust gas temperature. Additionally, the cylinder pressure and heat release rate are measured for successive cycles using a pressure transducer and ignition delay. The averaged values are calculated by amplifying the output signal of the pressure transducer, which is connected to the data acquisition system (refer to Fig. 2(a)). To measure the level of carbon monoxide (CO), unburned hydrocarbon (UHBC), nitric oxide (NOx), and smoke opacity, an AVL Digas 444 exhaust gas analyzer is used (refer to Fig. 2(b)). It extracts exhaust gas samples and measures concentrations of key pollutants like hydrocarbons, carbon monoxide, nitrogen oxides, carbon dioxide, and smoke opacity. The analyzer converts gas concentrations into electrical signals, determining the exact levels of each gas. It displays real-time results on its screen, allowing users to monitor emissions immediately. The analyzer is calibrated with reference gas for accuracy. The smoke opacity is determined using the AVL 437 smoke meter.

Table 2. Properties of Blends as per ASTM standard

Sample	Density at 25°C	LCV Calorific Value	HCV Calorific Value	Flash Point	Fire Point	Kinematic Viscosity @40°C	Dynamic Viscosity @40°C
Unit	kg/m^3	kJ/kg	kJ/kg	°C	°C	cSt	cP
ASTM Std	D287	D4809	D4809	D93-58T	D93-58T	D445	D445
Std Diesel	816	42987	45448	53	56	2.09	1.73
B100	851	37245	39709	125	141	4.2	3.5
B20	820	39875	41142	63	51.6	3.33	2.6
B30	845	38956	41160	62	52.3	4.05	3.2
B40	789	38967	41652	61	58.3	4.06	2.8
B20 GNP50	785	39685	40890	68	59.3	4.02	2.1
B20 GNP75	805	68595	40263	52.6	58.6	4.56	2.2
B20 GN100	720	39658	41180	52.3	57.4	4.22	2.6
B30 GNP50	800	39867	41416	61	58.3	4.3	2.8
B30 GNP75	850	29850	41526	61.8	56.8	4.2	2.9
B30G NP100	850	29850	41526	61.8	56.8	4.2	2.9
B40 GNP50	750	39685	41592	56.2	54.5	3.8	2.8
B40 GNP75	864	36987	40280	59.2	54.2	3.8	2.7
B40 GN100	824	36894	41280	56.3	51.2	3.2	2.4

Table 3. Specification of Diesel Engine

Description	Specification
No. of cylinder	1
Stroke	4
Cylinder Diameter	87.5 mm
Stroke Length	110 mm
Connecting rod length	234 mm
Orifice Diameter	20 mm
Dynamometer arm length	185 mm
Power	3.5 kW
Speed	1500 RPM
Compression Ratio	18.1
Swept volume	661.45 cc

(a)

(b)

Figure 2. (a) Engine Test ring, and (b) Emission Gas Analyzer (AVL 437).

The experimental test was conducted on a commercial single-cylinder diesel engine operating at a constant speed of 1500 rpm. The injection pressure was 216 bar, and the injection timing was 26º TDC. The engine was started under no load condition and allowed to warm up for the rated speed of 1500 rpm with a compression ratio of 18:1, and readings were taken under steady-state conditions. The actual experimental setup is shown in Fig. 2(a). During the experiment, the load varied from 0% to 100% in increments of 25%. The trials were repeated for blends of D100, B20, B30, and B40, both with and without mixing GNPs at concentrations of 50, 75, and 100 ppm. Repeat readings for the same blends were carried out to verify the accuracy of the findings. I used a data acquisition system to record various performance parameters.

3.1 Error Analysis

An error or uncertainty analysis is necessary to verify the accuracy of measured parameter values. This uncertainty may arise from faults in the measuring instruments, vibrations, loose connections, calibration, etc. Therefore, uncertainty analysis is crucial to validate the accuracy of the results. Uncertainty in measured performance parameters can be evaluated using Equation (1) through the root mean square method. The overall uncertainty (Ut) of the total measured quantity 'n' has been determined, which depends on the independent variables x1, x2, ..., xn, along with associated errors Δx1, Δx2, ..., Δxn. Furthermore, the percentage of uncertainty for the BTE and SFC parameters was found to be 2.04% and 3.64%, respectively.

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

4. Result and discussion

The test involved running the engine at 25%, 50%, 75%, and 100% load using pure diesel and soybean biodiesel, with and without GNPs, while maintaining a constant speed and compression ratio. The performance and emission characteristics have been assessed, and the results are presented in this section to analyze the impact of different loads on biodiesel blends.

4.1 Brake Thermal Efficiency

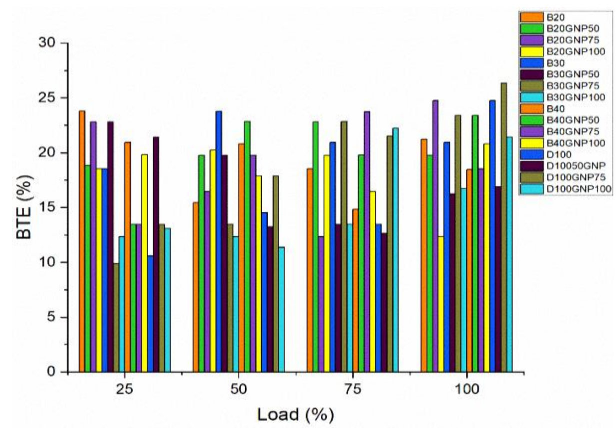

Figure 3. Variations of load vs. brake thermal efficiency

Figure 3 illustrates the brake thermal efficiency (BTE) findings for different loads of pure diesel and soybean biodiesel with and without GNP blends. Initially, at a 25% load condition, BTE is lower for all the blends except B20GNP75. As the load is increased from 25% to 100%, the BTE improves for all the cases. In comparison to biodiesel mixed with GNPs, GNP75, and B20GNP75 show higher BTE, which increased when the GNPs were added from 50 ppm to 100 ppm in GNP75 and B20. This improvement may be attributed to the higher load conditions. Higher loads and GNP concentrations in the diesel result in an increase in thermal efficiency. Similar behaviors were observed for all the blends. For blend D100GNP75 at full load, the Brake Thermal Efficiency (BTE) is 43.27%, which is higher compared to pure diesel. B20GNP75 shows a BTE of 27.49% at full load, also outperforming pure diesel. The remaining blends show improvements at complete load conditions, with B40, B30, and B20 with GNPs at 75 ppm concentration exhibiting BTE of 13.64%, 18.52%, and 21.13% respectively, compared to pure

Fig3. Variations of load vs Brake Thermal Efficiency diesel. Overall, it's evident that the BTE of D100 and B20 with GNPs is higher than that of pure diesel. This is attributed to the combined effect of oxygen available in diesel and biodiesel, and the thermal properties of GNPs, resulting in efficient combustion of the fuel.

4.1 Brake-specific fuel consumption

The study evaluated brake-specific fuel (BSFC) consumption under varying loads. The results are depicted in Figure 4, showing the fuel consumption for different blends and pure diesel. It was found that B20GNP75 and D100GNP100 fuels consume less fuel mass than other cases at higher loads due to their higher calorific value and lower viscosity. Soybean oil-based biodiesel burns more efficiently than gasoline fuels at higher load conditions. In particular, blend B20GNP75 consumes less fuel than diesel under full load compared to other loads, attributed to increased specific area, improved fuel flow tendency, Additionally, it was observed that B20GNP100 exhibits higher fuel consumption at full load. Overall, at a full load of 12 kg condition, BSFC values for B40, B30, B20, and D100 with and without GNPs were found to be 8.46%, 10.13%, 12.24%, 13.21%, and 11.21%, 12.64%, 13.63%, 14.64%, respectively. These values are lower compared to diesel. It was also noted that the compression-ignition engine consumes more fuel energy with increasing load for all fuel types.

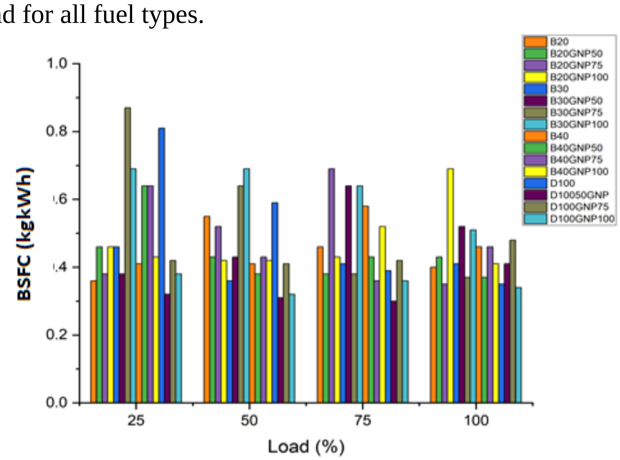

Figure 4. Variations of load vs. brake-specific fuel consumption.

4.2 Unburnt Hydrocarbon

The impact of engine type and fuel type on unburnt hydrocarbon (HC) emissions is illustrated in Figure 5. The results indicate that, at a constant engine speed, B20 and B20GNP50 exhibit the lowest emissions at 25% load. This is attributed to the addition of GNP in biodiesel at 50 to 100 ppm to the biodiesel blend. The enhanced catalytic activity of nanoparticles increases the surface area to volume ratio, leading to greater energy production inside the cylinder.

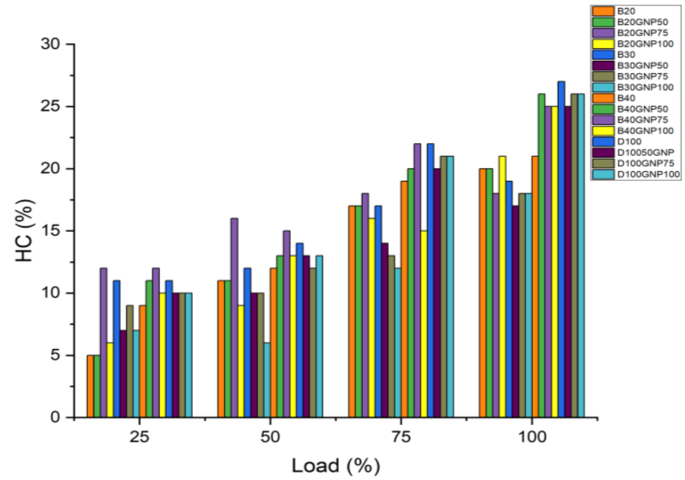

Figure 5. Variations of HC at variable load conditions.

4.3 Carbon Monoxide (CO) emissions

Figure 6, the graph illustrates the change in carbon monoxide (CO) emissions as the load varies for soybean biodiesel and Diesel with and without GNP additives. The graph shows that as the load increases and the concentrations of GNPs increase, the CO emissions for biodiesel blends decrease, particularly at 75% to 100% of the load. At these load levels, the CO emissions for biodiesel blends are lower than those for B40GNP100, D100, and D100GNP100 blends. The percentage variation in CO emissions compared to D100 is 51.41%, 37.86%, and 23.26% without GNPs, and 64.82%, 47.63%, and 38.73% with GNPs, for B30, B40, and B20 blends, respectively, at 100% of the load

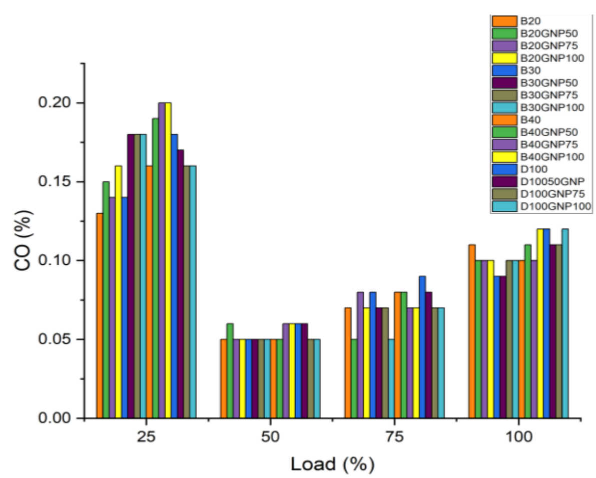

Figure 6. Variations of CO emission with varying load

4.4 Carbon dioxide (CO2) emissions

The impact of a variable load on CO_2 emissions is illustrated in Figure 7. CO_2 emissions were found to be higher in fuel mixtures B40GNP100, B40GNP50, and B40 than in the biodiesel B20 and D100GNP75. This is due to the complete combustion of fuel in the engine. The results indicate that combining nanoparticles with diesel and biodiesel, using a single fuel with 50 to

100 parts per million by volume of GNPs, leads to higher CO_2 emissions for all load conditions for B40 with and without GNP blends. However, adding GNP beyond 40% of soybean biofuel in diesel has adverse effects on CO_2 emissions. This suggests that the thermal properties and surface area will not be effective beyond this combination.

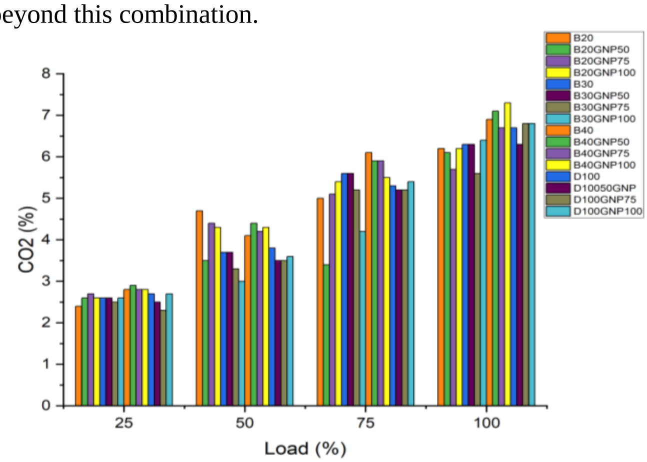

Figure 7. Variations of CO2 emission with varying load.

4.5 Nitrogen Oxide (NO_x) emissions

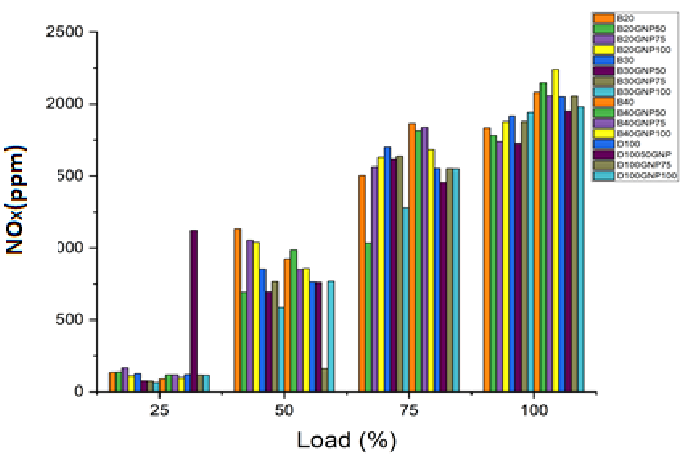

Figure 8. Variations of NOx with load conditions.

The Figure 8 shows the relationship between the variable load and NOx emissions for diesel and biodiesel with and without GNP. In metropolitan areas, motor vehicle traffic contributes significantly to air pollution due to the release of large amounts of nitrogen oxides into the atmosphere. The reason for detecting 4 times more NOx emissions at the 25% loading condition with D10050GNP compared to other fuels could be attributed to several factors. Firstly, the presence of 50 ppm graphene nanoplatelets (GNPs) in D100 (diesel) enhances thermal conductivity and combustion efficiency, leading to localized high combustion temperatures, which promote NOx formation. At lower loads, the fuel-air mixture tends to be leaner, creating favorable conditions for NOx emissions due to excess oxygen and elevated peak temperatures. Additionally, the improved oxidation rate and flame propagation caused by the GNPs may result in quicker energy release and higher in-cylinder temperatures. Non-uniform dispersion of GNPs at low loads may further cause temperature spikes or hot spots, exacerbating NOx formation. Overall, the combination of enhanced thermal properties, lean combustion characteristics, and localized temperature increases at partial load conditions likely explains the significant rise in NOx emissions for D10050GNP. The study indicates that NOx emissions increase as the load increases for variable fuel blends, especially in the presence of GNP. This is attributed to the lower combustion chamber temperature maintained by GNP additives in biodiesel compared to pure diesel. For B30, B20, and B40 blends with and without GNPs, the study found increases in NOx emissions compared to pure diesel at higher loads. Specifically, the NOx emissions increased by 2.68%, 4.23%, 14.83%, and 19.81% for B30, B20, and B40 blends without GNP, while the increases were 12.38%, 15.67%, 26.26%, and 41.86% for the same blends with GNP. Overall, the research concluded that B40GNP100 fuel exhibited the highest NO_X emissions compared to all other fuel blends and pure diesel.

4.6 Smoke Opacity (HSU)

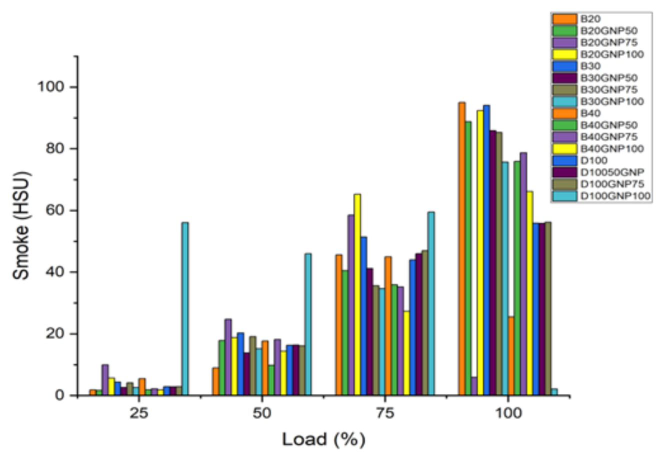

Figure 9. Variations of smoke emission with load conditions.

The study evaluated the smoke opacity of different fuels at various engine load conditions, as shown in Fig. 9. The results indicated that smoke opacity increased with higher engine load. However, there was a significant reduction in emissions for B20GNP75 and B40 compared to other fuels, particularly at full load (100%). This suggests that adding GNP to soybean biofuel helps decrease smoke opacity compared to pure diesel. At 25% load, the D100GNP100 had the highest smoke opacity, aside from B20, B30, and B40 with and without GNPs. The addition of GNP in biofuels contributes to carbon oxidation through the combined effect of oxygen and thermal properties. At full load, the blends B20, B40, and D100 with GNP had smoke opacity of 26.45%, 37.12%, and 67.91%, respectively, compared to pure biodiesel and diesel. For 25% load conditions, the smoke opacity was 13.25%, 15.61%, and 17.83%, respectively.

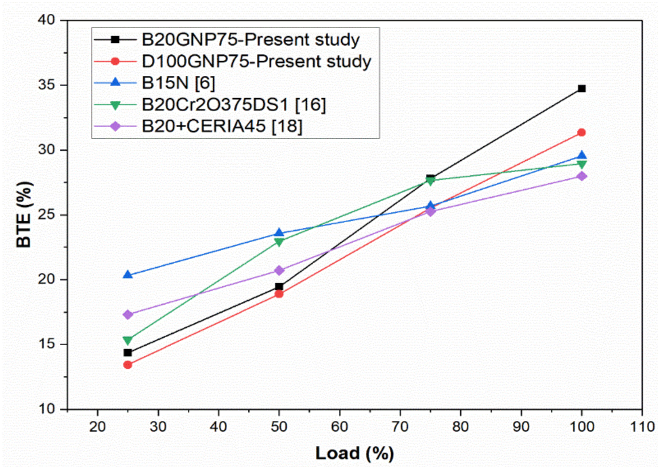

Figure 10. Comparative graph of reported studies for different blends with present work at variable load conditions.

4.7 Comparative Study

Figure 10 compares the reported work for different blends with the present study for BTE at variable loads. The considered reported study blends are as follows: - B15N: 15% spirulina biofuel + 85% diesel - 75 ppm Al2O3 [16] - B20Cr2O375DS1: 20% linseed biodiesel + 80% diesel and Chromium oxide 75 ppm [16] - B20+CERIA45: 20% waste cooking oil + 80% diesel with 45 ppm of cerium oxide [18]. The BTE results from these blends were higher in their work. After comparing the reported studies, it was observed that B20GNP75 shows improvement by 17.56%, 19.96%, and 24.08% compared to the reported studies [6, 16, 18], and D100GNP75 shows enhancement by 6.09%, 8.25%, and 11.96%, respectively. This indicates that adding GNP helps improve BTE and reduce emissions compared to the reported studies [6, 16, 18]. This improvement is due to the combined effect of oxidation and GNP thermal properties in soybean biodiesel and diesel. Several aspects should be considered while comparing effects of adding 75 ppm nanoparticles from different materials to B20 fuel on brake thermal efficiency (BTE), Graphene nanoplatelets (GNPs), cerium oxide (ceria), and other nanoparticles, such as alumina or titanium dioxide, influence BTE through different mechanisms. GNPs, due to their excellent thermal conductivity, improve heat transfer and enhance combustion efficiency, leading to a significant increase in BTE at higher loads, as observed in the present study. In contrast, ceria nanoparticles act as combustion catalysts, enhancing oxygen availability and reducing ignition delay, which improves combustion but may show diminishing returns at higher loads. The variations in BTE across different nanoparticle materials also depend on their ability to reduce ignition delay, enhance air-fuel mixing, and optimize flame propagation, especially at low and medium loads. GNPs in the present study (B20GNP75) demonstrate a steeper rise in BTE at higher loads compared to ceria and other additives, likely due to their superior thermal properties. A comparative analysis at similar concentrations and load conditions will help identify which nanoparticle provides the most consistent and significant improvement in BTE for B20 fuel blends, enabling better optimization for practical applications.

5. Conclusion

In the results and discussion section, we explore the findings based on various blends with and without GNPs in soybean biofuel and pure diesel. These blends were tested under variable load conditions at a constant speed and compression ratio. After thoroughly examining the results and discussing them, the following conclusions have been drawn:

- The D100GNP75 and B20GNP75 blends achieve the highest brake thermal efficiency (BTE) at full load, with 43.27% and 27.49% respectively, compared to pure diesel.
- The B20GNP75 and D100GNP100 blends have the lowest brake-specific fuel consumption (BSFC) at 25% load compared to pure diesel. However, at loads higher than 12 kg, diesel has lower BSFC. It seems to be inconsistent. It may be because of engine might have been temporarily overloaded beyond its rated capacity, though this can lead to inefficiencies or inaccuracies in the measurements. Alternatively, the study may involve engine modifications, such as changes to the fuel injection system, turbocharging, or intake pressure adjustments, to simulate higher loads. Another method could involve using a dynamometer to artificially simulate loads beyond the engine's nominal capacity, even if these conditions are not practical for real-world operation. Additionally, the use of fuel blends or additives, such as nanoparticles in biodiesel, may enhance performance and allow testing under conditions that simulate higher loads. If data from a different engine or testing setup with a higher capacity was used for comparison, this must be explicitly stated to avoid confusion. Clarifying the method for achieving loads beyond 12 kg is essential to ensure consistency, reliability, and reproducibility of the results.
- The emission levels of biodiesel and diesel blends are under control compared to pure diesel, indicating that GNP-blended fuels could play a significant role in internal combustion engine applications in the future.
- Compared to previous studies [6, 16, 18], the BTE (%) for the B20GNP75 and D100GNP75 blends show an improvement of approximately 20.53% and 8.76%, respectively. This is attributed to the combined effect of carbon oxidation at higher temperatures and the thermal properties of GNP in soybean biofuel and diesel.

Nomenclature

AL_2O_3	: Aluminium Oxide Nanoparticles
BTE	: Break Thermal Efficiency
BSFC	: Break Specific Fuel Consumption
CeO_2	: Cerium Oxide Nanoparticles
CIB	: Cinphyllum
GNP	: nanoplatelet
TF	: Ternary Fluid

Conflict of Interest

The authors have declared no conflict of interest.

Credit Author Statement

Prakash Kadam- Formal analysis, methodology, validation, investigation, writing original draft;
Dhanajay Dolas- supervision, and project administration;

Reference

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