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RESEARCH ARTICLE

Impact of Soybean Biodiesel Blends with Mixed Graphene Nanoparticles on Compression Ignition Engine Performance and Emission: An Experimental and ANN Analysis

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ABSTRACT - The extensive use of fuels in power generation plants, industries, and transportation has led to a scarcity of fossil fuels and has contributed to global warming. This has prompted researchers to focus on improving internal combustion engine performance, as the transportation system accounts for 50% of global fuel consumption. Soybean biodiesel plays a vital role in reducing emissions and fuel consumption in engines. In the current work, a blend of soybean oil is used as a biodiesel (B20, B40, and B60), with and without the addition of graphene nanoplatelets (GNPs) examined on a constant-speed compression ignition engine with respect to pure diesel. The blends are denoted as B20GNP10, B20GNP20, B20GNP40, B20GNP60, B20GNP80, and B20GNP100, according to their proposition of biodiesel and graphene nanoplatelets. Similar blends were prepared for B40 and B60 combinations with similar GNPs concentrations. The prepared blend properties were measured, and good thermophysical properties were found. The trial includes testing the engine emissions and performance at altering loads ranging from 0 to 12 kg for all blends. The artificial neural network (ANN) tool is used to forecast the accuracy of experimental results. Compared to pure diesel, the B60GNP100 blend at 12 kg load condition showed the lowest brake specific fuel consumption at 12.58 % and the highest brake thermal efficiency at 27.13%. Emissions were estimated using a gas analyzer, and the outcomes indicated that the biodiesel blends have controlled levels of CO, CO_2, NOx, and HC compared to pure diesel. The ANN model with 99.99% accuracy was developed using experimental data, confirming the accuracy of the experimental results with lower simulation time and cost. Additionally, the B60GNP100 blend yielded better results compared to previous studies.

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1. INTRODUCTION

Effective energy conversion and availability are crucial for any country's economy. Diesel engines are vital in agriculture and transportation, offering higher brake thermal efficiency (BTE), compression ratio, cetane number, and lower brake-specific fuel consumption (BSFC). The increasing demand for power, depleting fossil fuel reserves, and environmental concerns are driving researchers to seek alternative fuels for diesel engines. It addresses the sustainability challenges and reduces emissions [1-3]. Biodiesel fuels are considered promising alternative fuels nowadays. They are used in diesel engines to minimize exhaust emissions and improve engine performance [4-6]. Recently, ethanol, methanol, and butanol have been combined with diesel to create biodiesel blends. However, alcohol-based fuels have certain drawbacks, such as low Cetane numbers, high ignition temperatures, and low thermal values [7-9]. They also have higher corrosion, volatility, color and pour point, and higher water absorption rates [7-9]. To address these issues, many researchers are exploring the accumulation of nanoparticles in biodiesel fuels [10, 11] to compensate for the thermophysical drawbacks of these alcohol-based blends.

Many studies have been conducted on the impacts of adding nanoparticles to fuels to remove the adverse influences of ethanol and biofuel on diesel fuel [12, 13]. Blending biodiesel with nanoparticles would reduce greenhouse gases and improve compression ignition (CI) engine performance and emission [14, 15]. Many of them use metal nanoparticles, including zinc, cerium, copper manganese, and iron, as additives for fuel [16, 17]. While using various nanoparticles to analyze aluminum oxide (Al_2O_3) and ricinoleic acid, the fuel is prepared using correlations of colloidal particles and additives of 10, 20 and 50 ppm. Results show a reduction in the temperature of the cylinder and an improvement in the delay of ignition [18]. Moreover, various research studies have concluded on the combustion behavior of diesel engines in dual fuel mode.

In the first mode, nanoparticles are created by using an ultrasonicator and converted homogenizer mixed with dairy scum oil methyl ester (DSOME) in a mass fraction of 10 to 30 ppm. The outcome demonstrates reduced brake BTE, hydrocarbon, and carbon monoxide (CO) by 11.5 %, 23.2 %, and 32.6 %, respectively, during a load of 80 % [19]. The solution of B20 was combined with concentrations of 50, 75, and 100 ppm of chromium oxide nanoparticle addition and

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dispersion at a persistent speed of 1500 rpm during the experimentation. They were using gasoline treated with nanoparticles that significantly enhanced net heat release rate (NHRR) and cylinder pressure (CP). Moreover, BTE rose, and BSFC was reduced [20]. The influence of Al_2O_3 nanoparticles on flame properties, pollutant emissions, and thermal performance 20 % palm oil biodiesel added with Al_2O_3 nanoparticles has temperature radiation, flame characteristics, and pollutant emission in the burner. B20 with Al_2O_3 nanoparticles tend to reflect heat rather than absorb it [21]. The response surface method improves the engine's performance by using 40 to 160 ppm aluminum nanoparticles in steps of 40 ppm at various engine speeds. Maximum torque and brake power of 402.8 Nm reduce the BSFC and emissions. [22]. The CP and NHRR of the biodiesel blend were lower using the fatty acid structure of Egyptian jatropha seeds oil B100, B80, B60, B40 and B20 volumetric blend of biodiesel [23]. Cerium oxide (CeO_2) was examined as an emission control approach in jatropha biodiesel blending with alumina and CeO_2 nanoparticles 10, 30 and 60 ppm, resulting in reduced emissions of CO, carbon dioxide (CO_2), smoke, and unburnt hydrocarbons (UHC) by 60 %, 13 %, 32 %, and 33 %, respectively [24]. In the concentration of CeO_2 nanoparticles with jojoba biodiesel fuel 25, 50 and 75 ppm, results show that JB20CN50 fuel has a more excellent BTE than the other sample of jojoba biodiesel fuel [25].

Some of the works elaborating on direct-injection (DI) engine systems are as follows: The DI diesel engine biodiesel blend nanoparticles that may have an effect (B20) were supplemented with Copper (II) chloride and Cobalt (II) chloride nanoparticle concentrations of 50, 75 and 100 ppm, respectively. Nanoparticles were given a 100 ppm dose of QPAN 80 dispersion, which was then ultrasonically processed. Day 1 and Day 15 were chosen specifically for the stability test [26]. Also, some of the researchers conducted studies to enhance the thermal and physical properties of the fuel. Various additives, such as nanoparticles and water emulsions, are added, and analysis is carried out to see how engine performance parameters change over time. A.I. El-Seesy *et al*. [27] performed the studies on the graphene oxide (GO) particle blending with diesel with n-octanol and n-butanol-heptanol 50 and 25 mg/l percentages at a constant speed of 1000 rpm. They observed reduced smoke by 30 %, CO by 40 %, UHC by 50 %, BTE by 15 %, and NHRR by 4 %. G. Pullagura *et al*. [28] found better results by using dimethyl carbonate (DMC) of 10 % in B30 biodiesel in the concentration of 30, 60, and 90 ppm of graphene (G) nanoparticle at a 1500 rpm constant speed of CI engine. Outcomes show an increase in BSFC, increased NHRR by 9.63 %, B30DMC10 reduced by 15.45 %, CO reduced by 22.87 %, and slightly increased nitrogen oxide (NOx) by 9.57%. M. E. Pireh *et al*. [29] examined the blending of 5 % and 20 % biodiesel of waste cooking oil in 30, 60 and 90 ppm of GO nanoparticles, increasing NOx and CO_2.

H. Khan *et al*. [30] used the blend of nigella sativa (NS) biodiesel with n-butanol and synthesized asymmetric GO nanoparticle concentrations of 30, 60, 90 and 120 ppm. The blend of NSME 25B10GO90 improves the BTE, BSFC, and emission contents of the CI engine. M. Elkesley *et al*. [31] studied waste-cooked oil blends with nanoparticles such as B40, B40-GO, and B40-CNTs with concentrations ranging from 50 to 150 ppm, respectively, for CI engines. Blends are considered to enhance evaporation, oxygen rate, and surface area. They are ensuing in condensed NOx at maximum load and 46.3 % BTE. B40-CNTs and B40-GO show superior engine attributes compared to B0 and B40 without additives. L. Razzaq *et al*. [32] investigated the impact of biodiesel blends with 10% v/v DMC and graphene oxide nanoplatelets (GNPs) as additives on engine performance and emissions. Palm biodiesel was used, 30 % with diesel, and GNPs were added at 40, 80 and 120 ppm concentrations using the ultrasonication technique. Sodium dodecyl sulfate (SDS) surfactant is used for stability. The B30GNP40DMC10 blend shows a maximum reduction in BSFC by 5.05 % and improves the BTE by 22.80 %. CO, HC, and NOx were reduced by 4.41 %, 25 %, and 3.65 %, respectively, showing a significant reduction in the average coefficient of friction, indicating the potential for diesel engine optimization.

A. Heidari-Maleni *et al*. [33] studied the influence of incorporating graphene quantum dot (GQD) nanoparticles into ethanol-biodiesel blends to explore the performance of a diesel engine. A biodiesel was included in a B10 blend, and GQD nanoparticles at 30 ppm of concentration were tested with independent blends. Experimental trials were conducted at variable engine speeds, i.e., 1800 - 2400 rpm, and the finding indicates that the addition of GQD to fuel resulted in a notable increase in torque and power by 12.42 % and 28.18 %, respectively. Furthermore, SFC, UHC, and CO are reduced by 14.35 %, 31.12 %, and 29.54 %, respectively, linked to pure diesel. In an experimental study, S. Debbarma [34] investigated the impact of adding commercially available graphene to transistorized palm oil biodiesel in a CI engine. An ultrasonication process created blends at 50, 75 and 100 ppm dosing levels. Emissions of UHC decreased by 17 % and CO by 34 %, while NOx increased slightly by 3.8 % and an increase in BTE by 2.5 %. S. A. Ali *et al*. [35] explored the influence of CeO_2 and Magnesium oxide nanoparticles distributed in waste cooking oil (WCO) biodiesel on the BTE performance of a variable compression ratio CI engine. The nanoparticle is dissolved with biodiesel blends with B20, B40, and B60 concentrations using an ultrasonication method. Tests were performed at 1500 rpm, and load ranged from 25 % to 100 %, resulting in a decrease in CO, NOx, and CO_2.

A. I. EL-Seesya *et al*. [36] inspected the influence of GO nanoparticles on neat jatropha methyl ester (JME) in a CI engine. The considered concentration was 25 to 100 mg/l of JME-GO used. Results show a 17 % hike in BTE, 8 % higher peak CP, and a 6 % increase in maximum NHRR. Meanwhile, UHC, CO, and NOx decreased by 50 %, 60 %, and 15 %, respectively. The most noteworthy gain in emission and performance was observed at 50 mg/l of concentration in JME-GO. K. Subramani, and M. Karuppusamy [37] studied the WCO as a biodiesel (i.e., 20 % with diesel). The CeO_2 nanoparticle mixed with biodiesel by ultrasonication ranged from 15 to 75 ppm, which resulted in an enhancement of 3.62 % thermal efficiency, SFC decreased by 3.3 %, and there was a decrease in NOx. S. Kumar *et al*. [38] evaluated the emission and performance of a CI engine at a 1500 rpm constant speed by using Pongamia 20 % as biodiesel with the addition of 0.5 - 1.5 % Ferrofluid nanoparticles. While using B20, adding 1 % of ferrofluid decreases CO by 35.38 %, and HC is lowered by 22.9 % at 100% on engine load. The addition of ferrofluid decreases BSFC by 8 % to 0.5 %. Some of the literature studies based on nanoparticles are discussed in Table 1.

Table 1. Detailed literature based on Graphene (G) nanoparticles in base fuel

Nano-Material	Engine Type (Diesel)	Engine test condition	Testing fuel	Performance Result (%)	Emission Result (%)	Ref.
GO nanoparticles	CI Engine	0, 25, 50, 75, and 100%; 2100 rpm	Oenothera Lamarckiana Biodiesel; GO (30, 60, 90 ppm)	BTE ↓, BSFC ↑	CO (5 - 22) ↓, UHC (17 - 26) ↓, CO_2 (7 - 11) ↑, and NOx (4 - 9) ↑	[10]
GO	direct injection (DI) and water-cooled (W-C) CI engine	Full Load; 2400 rpm	DSOME and SDS; 20 to 60 ppm of GO	BTE - 11.056 ↑, BSFC -8.34 ↓	CO (38.62) ↓, UHC (21.68) ↓, NOx (5.62) ↓, CO_2 (24.88) ↓.	[13]
GO, GNPs, and multiwalled carbon nanotubes (MWCNTs)	air-cooled (A-C) DI Engine	0, 3, 6, 9, and 12 kg, and 13.5 N·m; 2000 rpm	60 % (by vol.) JME 40 % n butanol fuel; MWCNT of 50 mg/l	BSFC- 22 ↑, Peak cylinder Pressure (PCP) - 6 ↑, SFC 35 ↓	CO (60) ↓, UHC (50) ↓, NOx-(15) ↓	[36]
CeO_2, GO, and single- WCNTs	A-C (light-duty HATZ 1B30) CI engine	2.9, 12.3, and 14.4%; 2000 rpm	25 ppm of CeO_2, GO, and SWCNTs	BSFC - 15.2 ↑, ID - 10.3 ↑	CO - 23.4↓ and UHCs - 24.1↓	[39]
GO	W-C CI engine	80 % of full loads; 1500 rpm	Simarouba methyl ester (SME); GO 20, 40, 60 ppm	BTE - 9.14 ↑	HC - 15.38↓, CO - 42.85↓, and NOx - 12.71↓	[40]
GO, 50 mg/l GNPs, MWCNTs	W-C CI engine	0, 3, 6, 9, and 12 kg; 13.5 N·m; 2000 rpm	Neat JME; 50 mg/l of GO, GNPs, MWCNTs	BSFC-22 ↑, PCP 6 ↑, SFC-35 ↓	CO (55) ↓, UHC (50) ↓, NOx (45) ↓	[41]
GNPs	A-C CI engine	0, 3, 6, 9, and 12 kg; 13.5 Nm; 1500, 2000 and 2500 rpm	20% JME; GNPs 25 to 100 mg/l	BSFC- 20 ↓, PCP – 6 ↑, highest rate of pressure rise -5 ↑, Max. NHRR - 5 ↑, BTE – 25 ↑	CO (60) ↓, UHC (50) ↓, NOx (40) ↓	[42]
GO	A-C DI Engine	0, 25, 50, 75, and 100 %; 2100 rpm	Ailanthus altissima biodiesel B0, B10, B20; 30, 60, and 90 ppm of GO	SFC by 14.48 ↓ for B20G90	CO (7- 20) ↓, UHC (15 -28) ↓ and NOx (5 -8) ↑, CO_2 (6 -10) ↑	[43]
GO	A-C DI Engine	0, 3, 6, 9, and 12 kg; 13.5 N·m; 2000 rpm	JME; 25, 50, 75 and 100 mg/l of GO	BTE – 17 ↑, NHRR – 8 ↑, 6 ↑	CO (60) ↓, UHC (50) ↓, NOx (15) ↓	[44]
GO	W-C CI engine	25 – 100 %; and 1500 rpm	rice bran oil blend of B5D95 and B15D85; 30 ppm GO in each blend	BSFC 13.5 ↓, BTE 7.62 ↑	CO, CO_2 and NOx - 2 to 8 ↓	[45]

It was observed that using biodiesel in CI engines does not enhance engine performance, lower fuel combustion, or reduce gas emissions. However, it shows that adding nanoparticles to the base fluid or blends lessens emissions and boosts the performance of CI engines. It has been noticed that very few researchers have explored the use of graphene nanoplatelets (GNPs) combined with soybean biodiesel to analyze the performance and emission characteristics of an engine. This study experimentally evaluates the impact of diverse soybean biodiesel blends with varying concentrations of GNPs and pure diesel on a CI engine's performance and emission characteristics under varying load conditions at a constant engine speed and compression ratio. The study compares the experimental outcome results with the predicted results obtained using the Artificial Neural Network (ANN) technique. Finally, the study compares the results of the best-performing blends with those of previously reported biodiesel studies. Furthermore, the paper consists of various sections that deal with the experimental method, ANN modeling, experimental results and discussion, and conclusion.

2. EXPERIMENTAL METHOD

2.1 Preparation of Biodiesel

An analytical grade of soybean oil is used in this study. The choice of soybean biodiesel is based on its ready availability in the Indian market and abroad, its economic viability, environment-friendly properties, high oil content, support for agricultural infrastructure, and government financial incentives. Additionally, soybean biodiesel emits lower levels of greenhouse gases, sulfur, NOx, particulate matter, CO, and UHC [46]. The fatty acid composition was carried out in a 500 ml borosilicate glass circular bottle flask. Before beginning the reaction, the oil was warmed to 55°C; at this movement, KOH solution was added to the oil under mechanical stirring at about 350 rpm, and a transesterification reaction was used to synthesize methyl ester. Reaction time is 1 hour. The methyl ester biodiesel purification process involved washing it with distilled water.

2.2 Preparation of Biodiesel Blend with GNPs nanoparticle

This work used graphene nanoplatelets (GNPs) as nanoparticles to blend with soybean biodiesel in concentrations of 10, 20, 40, 60, 80, and 100 ppm. Dispersion of GNP nanoparticles with fuel is done by ultrasonication and stirring using an ultrasonicator and magnetic stirrer apparatus for 45 min and 30 min, respectively, for dispersion of GNPs in biodiesel and to prepare the homogenous mixture of biodiesel blend of B20, B40, and B60 (i.e., B20 = Soybean biofuel 20% and diesel 80%, and similarly combination were used for other two biodiesel blends), see Figure 1 (a) and (b). To check the stability of the prepared test fuel, it is kept in a 100 ml glass tube at room temperature for 12 hours. The Thermal properties and GNP blends of diesel and biodiesel are being tested at Apex Innovations Pvt. Ltd. in Sangli, India, as per the ASTM standards and the outcomes are tabulated in Table 2. The properties of the blends show higher density, lower calorific value, higher flash and fire point, and viscosities than pure diesel. The blends are B100, B20, B20GNP10, B20GNP20, B20GNP40, B20GNP60, B20GNP80, B20GNP100 ppm and the same blend of B40 and B60. Where B20, 40, and 60 represent 20 %, 40 % and 60 % of soybean and GNP as graphene nanoplatelets of 10, 20, 40, 60, 80 and 100 ppm in biodiesel.

(a)

(b)

Figure 1. (a) Sample of diesel and biodiesel blends, and (b) process of adding nanoparticles in diesel and biodiesel blends

Table 2. Properties of Blends as per ASTM standard

Sample/ Properties	Density at 25°C	LCV Calorific Value	HCV Calorific Value	Flash Point	Fire Point	Kinematic Viscosity @400°C	Dynamic Viscosity @400°C
Unit	$kg/m3$	kJ/kg	kJ/kg	°C	°C	cSt	cP
ASTM Standard	D287	D4809	D4809	D93-58T	D93-58T	D445	D445
Std Diesel	816	42987	45448	53.0	56.0	2.09	1.73
B100	851	37245	39709	125.0	141.0	4.20	3.50
B20GNP10	820	39875	41142	63.0	51.6	3.33	2.60
B20GNP20	845	38956	41160	62.0	52.3	4.05	3.20
B20GNP40	789	38967	41652	61.0	58.3	4.06	2.80
B20GNP60	785	39685	40890	68.0	59.3	4.02	2.10
B20GNP80	805	68595	40263	52.6	58.6	4.56	2.20
B20GNP100	720	39658	41180	52.3	57.4	4.22	2.60
B40GNP10	800	39867	41416	61.0	58.3	4.30	2.80
B40GNP20	850	29850	41526	61.8	56.8	4.20	2.90
B40GNP40	750	39685	41592	56.2	54.5	3.80	2.80
B40GNP60	854	39698	40180	57.8	56.2	3.20	2.60
B40GNP80	864	36987	40280	59.2	54.2	3.80	2.70
B40GNP100	824	36894	41280	56.3	51.2	3.20	2.40
B60GNP10	846	36985	41260	61.0	53.4	4.10	3.60
B60GNP20	856	37890	41260	62.5	52.6	3.80	3.70
B60GNP40	824	38964	41560	58.4	51.0	3.60	2.50
B60GNP60	867	38562	40160	52.6	49.2	3.10	2.80
B60GNP80	725	37895	41560	53.4	48.2	3.80	2.40
B60GNP100	785	37892	41280	59.1	43.8	3.90	2.90

2.3 Experimental Setup and Procedure

The present study utilizes a single-cylinder, four-stroke CI (diesel) engine to assess performance and emission features (engine specifications are provided in Table 3). The CI engine is connected to an electric eddy current dynamometer and K-type thermocouples for loading and measuring exhaust gas temperature. The pressure transducer and ignition delay measure CP and NHRR for successive cycles. The measurements are obtained by amplifying the pressure transducer output signal connected to the DAQ system (See Figure 2(a)). Additionally, an AVL (model - Digas 444) exhaust gas analyzer (See Figure 2(b)) is utilized to measure the levels of CO_2, CO, UHC, and NOx. The exhaust gas analyzer helps to identify engine problems and supports engine diagnosis. It is also used to monitor the percentage of different gas emissions to ensure compliance with government environmental regulations.

Table 3. Configuration of CI Engine

Description	Specification
No. of cylinder	1
Swept volume	661.45 cc
Stroke	4
Cylinder Dia. (D_{cyl})	87.5 mm
Connecting rod length (l)	234 mm
Stroke Length (L)	110 mm
Dynamometer arm length	185 mm
Orifice Diameter	20 mm
Power	3.5 kW
Compression Ratio	18.1
Speed	1500 rpm

During the trial, a commercial CI engine runs at a stable speed of 1500 rpm. The injection timing and pressure are maintained at 26º TDC and 216 bar, respectively. The engine operates under no load conditions and is allowed to heat up to the rated speed of 1500 rpm, with a compression ratio of 18:1. The output values are then recorded under steady-state conditions. The actual test rig is shown in Figure 2(a). In a CI engine, load conditions refer to the force applied by the eddy current dynamometer to counteract the engine's power production. In our current study, we have applied varying loads ranging from 0, 3, 6, 9, and 12 kg to assess the engine's power under different load conditions. The load of 3 kg represents 25% of the total load, while the loads of 6, 9, and 12 kg represent 50%, 75%, and 100% (i.e., full load), respectively. The trials were repeated for all the soybean biodiesel blends of B20, B40, B60, B80 and B100 with and without mixing GNPs at 20, 40, 60, 80, and 100 ppm. Repeated readings for the same blends have been carried out to check the correctness of the findings. The commercial diesel engine runs continuously for 30 min for each load. A DAQ system was utilized to capture and record the different performance and emissions parameters.

(a) (b)

Figure 2. (a) Engine Test ring, and (b) Emission Gas Analyzer (AVL 444)

The Brake Thermal Efficiency (BTE) of the engine is calculated as shown in Eq. (1)

$$BTE = \frac{BP \ x\ 3600}{m_f x\ C_v} \times 100\% \tag{1}$$

where, brake power (BP) in kW, m_f is mass flow rate in kg/sec, brake specific fuel consumption (BSFC) in kg/J, and calorific value (CV) of diesel and biodiesel blends in kJ/kg are calculated, as shown in Eq. (2-4).

$$BP = \frac{2\pi NT}{60} \tag{2}$$

$$m_f = \frac{\rho\ x\ V}{\tau\ x\ 10^6} \tag{3}$$

$$BSFC = \frac{m_f\ x\ 3600}{BP} \tag{4}$$

ρ = density of fuels (Kg/m^3), and V = volume of fuels (m^3).

2.4 Error Analysis

An error or uncertainty analysis is needed to check the correctness of measured parameter values. This uncertainty can be generated by the measuring instruments' faults, vibrations, loose connections, calibration, etc. Henceforth, error analysis is vital to prove the correctness of the results. Uncertainty in measured performance parameters can be evaluated using Eqn. (5) [17], a root means square method. The overall uncertainty (Ut) of total measured quantity 'n' has been projected, which is dependent on the independent variables $x_1, x_2,\ldots,x_n$, also consuming errors such as $\Delta x_1, \Delta x_2,\ldots, \Delta x_n$. Furthermore, the percentages of the uncertainty of the BSFC, BTE, UHC, CO_2, CO, and NOx parameters were 1.64 %, 1.04 %, 2.21 %, 2.25 %, 2.33 %, and 2.95 %, respectively.

$$\Delta Ut = \sqrt{(\left(\frac{\partial U}{\partial x_1}\Delta x_1\right)^2 + \left(\frac{\partial U}{\partial x_2}\Delta x_2\right)^2 + \cdots \ldots . +(\frac{\partial U}{\partial x_n}\Delta x_n)^2)} \tag{5}$$

2.5 ANN Modelling

When evaluating the performance and emissions characteristics of a CI engine using the ANN model, it's important to understand the significance of statistical errors such as Mean Absolute Percentage Error (MAPE), Regression coefficients (R), and Mean Squared Error (MSE). These metrics provide accuracy and reliability when using the ANN tool, directly impacting the numerical optimization of engine performance and emissions characteristics [47-48]. It's vital to remember that MAPE, R, and MSE provide accuracy measurements for the scale of a data set in percentage. Lower MAPE and MSE values indicate higher accuracy in the input data sets and scales, while higher R values are needed to evaluate the model's correlation with the data set. This means that MAPE, R, and MSE of the ANN tool are reliable and universal and are able to deliver consistent performance metrics regardless of the engine's size or operating range. Accurate predictions help engineers optimize engines for better performance, improved fuel economy, and reduced emissions [47 - 48]. The statistical error findings, using the ANN tool based on the input parameters data sets, show optimal practical performance and reduced emissions content. This conclusion was drawn from evaluating MAPE, R, and MSE values using the ANN model. It significantly reduces practical time and costs, optimizes problem design, and allows for real-time monitoring, control, and validation of results.

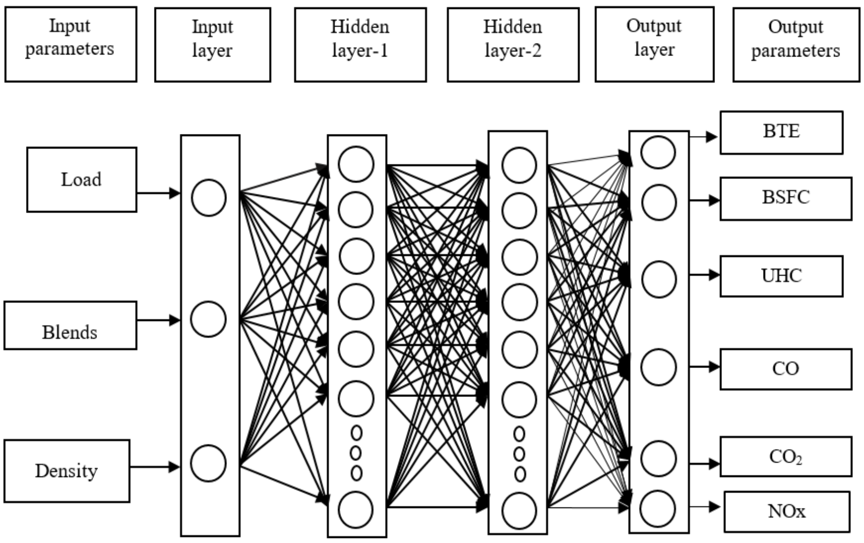


Figure 3. Arrangement of ANN Model

The ANN model has input, hidden, and output layers and is connected to the number of neurons with each other. In this model, the input layer information has been provided as input data, and it passes to the output layer through the hidden layer information. The present study adopts a feed-forward approach with a backpropagation learning algorithm to receive the minimum error in weighted space. To train the data in the ANN model load, soybean blends with and without GNPs, and the blend density have been considered as input parameters and BTE, BSFC, UHC, CO, CO_2 and NOx are set as output variables, as shown in Figure 3. Before training the data, the input parameter dataset is normalized from 0.1 to 0.9 using Eqn. (6). Whereas, in the normalized value $Z_{i,max}$ and $Z_{i,min}$ represents the maximum and minimum value of the dataset, and Z_n is a normalized value of Z_i. As soon as the input data is normalized, the ANN tool trains 70% of the dataset, while the remaining 15% of each dataset is allocated for testing and validation.

$$Z_n = 0.1 + \left[0.8 * \left(\frac{Z_{i,min}}{Z_{i,max} - Z_{i,min}}\right)\right] \tag{6}$$

2.6 Selection of Training Algorithm

In the present study, the MATLAB tool is adopted to run the ANN architecture. Based on studies conducted on the ANN tool, the choice of topology configurations and the number of hidden neurons is crucial, falling within the range of 2 to 25 [47 - 48]. Statistical errors, including MAPE (< 5%), R (> 0.98), and MSE (<0.001), are used to assess the performance of the ANN tool [47 - 48], as illustrated in Eqns. 7 - 9. The arrangement of the ANN model's topology is presented in Figure 3. The backpropagation learning algorithm has been considered in the ANN model, and it is developed with the Levenberg–Marquardt training algorithm (TRAINLM). This algorithm requires a considerable pace but provides the results in minimum time for training data sets. Also, the ANN model Log-sigmoid (logsig) transfer function is used to transfer data. In this study, ten neurons were carefully chosen for superior performance and correctness of the model. Training the data set may lead to validation errors; therefore, the data training was halted to minimize function loss.

$$R = \sqrt{(1 - \left\{\frac{\sum_{k=1}^{n}(T_k - O_k)^2}{\sum_{k=1}^{n} O_k^2}\right\})} \tag{7}$$

$$MSE = \frac{1}{n}\left\{\sum_{k=1}^{n}(T_k - O_k)^2\right\} \tag{8}$$

$$MAPE = \frac{1}{n}\left\{\sum_{k=1}^{n}\left(\frac{T_k - O_k}{T_k}\right)\right\} \times 100 \tag{9}$$

3. EXPERIMENTAL RESULTS AND DISCUSSION

The following section presents the results and discussions from tests conducted on a CI (diesel) engine. The tests were performed at a constant compression ratio and speed using variable blends of soybean biodiesel, with and without GNPs, as well as pure diesel. The engine was tested at different loads to assess the impact of the varying blends on the engine's BTE and BSFC. The results were obtained by comparing pure diesel with different blends of soybean biodiesel, with and without GNPs.

3.1 Brake Thermal Efficiency (BTE)

Figure 4 presents BTE for different loads of pure diesel and soybean biodiesel with and without GNP blends. Initially, at zero (0 kg) load condition, the BTE is lower for all the blends considered, but gradually increases as the load increases from 3 to 12 kg for all cases. When compared to soybean biodiesel mixed with GNPs, pure biodiesel shows lower BTE, but this improves after adding GNPs at concentrations ranging from 10 to 100 ppm in B20 to B60. The enhancement in BTE is due to the higher concentrations of GNPs in the biodiesel at higher load (i.e., 6 to 12 kg) conditions, and these trends were seen for all the blends mixed with GNPs.

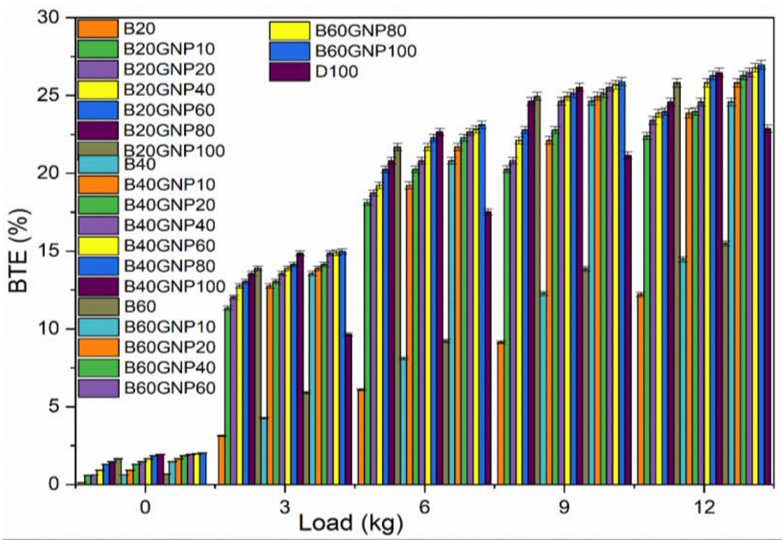


Figure 4. Impact of load on brake thermal efficiency (BTE)

The higher enhancement in BTE was 27.13 % for the B60GNP100 blend at 12 kg (full) load engine condition. The BTE values of B20, B40, and B60 with GNP100 were found to be 23.64 %, 25.52 %, and 27.13 %, respectively, which is higher than the pure diesel. In comparison, BTE values without GNPs in biodiesel were slightly lower than in pure diesel. Overall, biodiesel with GNPs exhibited higher BTE compared to pure diesel. The augmentation is due to the mixed impact of the oxygen available in biodiesel and the thermal properties of GNPs, which contributed to enhanced fuel combustion. The accumulation of GNPs in biodiesel improves the surface area and increases the premixing of the charge, which enhances the BTE.

3.2 Brake Specific Fuel Consumption (BSFC)

The BSFC for different loads was analyzed, and the findings are depicted in the graph for all the blends and pure diesel in Figure 5. The results reveal that pure diesel consumes less fuel mass than the other blends at higher loads due to its lower viscosity and higher calorific value. Soybean biodiesel burns completely and is more efficient than gasoline fuels under full load conditions. The B40GNP80 blend consumes less fuel than pure diesel at 6 and 9 kg loads due to increased surface area, improved fuel flow, and better atomization. It also improves combustion by reducing ignition delay and maintaining proper cylinder temperature and pressure. In general, at a higher load condition of 9 kg, the BSFC values for B20, B40, and B60 with and without GNPs were found to be 13.21 %, 12.24 %, 8.46 % and 14.64 %, 13.63 %, 11.21 %, respectively, which are lower compared to pure diesel.

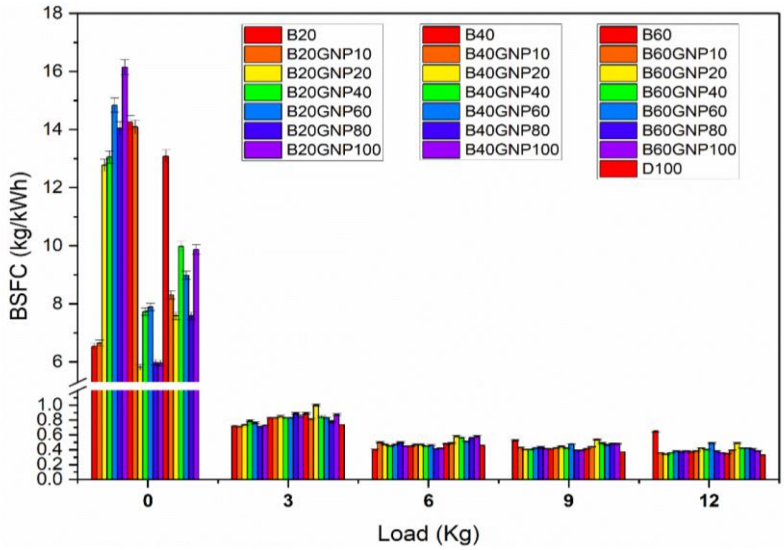


Figure 5. Impact of load on brake specific fuel consumption (BSFC)

3.3 Unburnt Hydrocarbon (UHC) Emissions

Figure 6 illustrates the impact of load and fuel type on UHC emissions. The result shows that at constant engine speed, B20GNP20 has the lowest emission of UHC at 3 kg of load. Also, the additives of GNP and Biodiesel at 10 to 100 ppm (i.e. 3 %, 6 %, and 12 % by vol.) to biodiesel blend. The high catalytic activity of nanoparticles raises the surface area to volume ratio, which boosts the power produced inside the engine cylinder. It is also observed that there is an increase in complete fuel combustion due to a rise in chemical processes, which helps in lessening pollutant emissions.

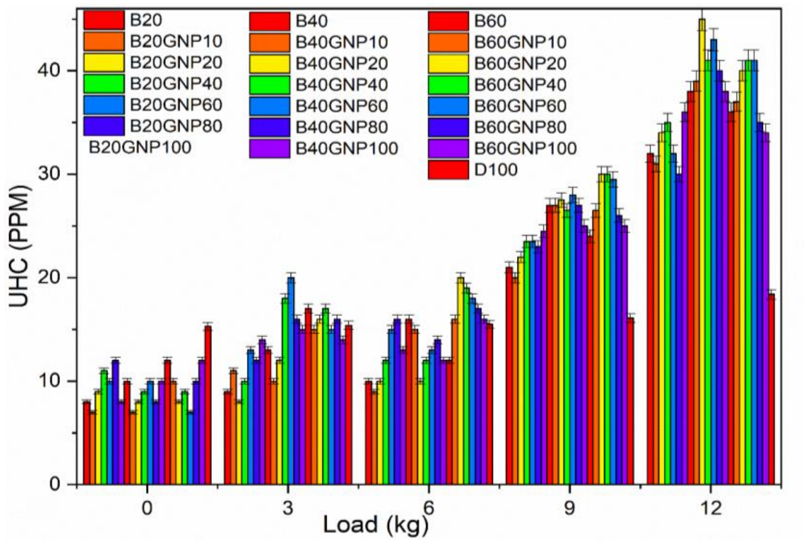


Figure 6. Variations of UHC at variable load conditions

3.4 Carbon Monoxide (CO) Emissions

The impact of varying load conditions and variations in fuel types on CO emissions can be seen in Figure 7. As the load increases for increased concentrations of GNPs, the CO emissions for biodiesel blends are reduced. There are fewer CO emissions than pure diesel. This variation in CO emission reduction than pure diesel was found at 18.41 %, 31.86 %, and 53.26 % without GNPs and with GNPs are 24.82 %, 37.63 %, and 58.73 % for B20, B40, and B60 blends, respectively. To improve fuel efficiency and combustion, researchers added nanoparticles to diesel and biodiesel in order to enhance combustion in CI engines. The accumulation of nanoparticles, especially GNPs, led to an increase in cylinder pressure (CP) because of their higher thermal conductivity and larger surface area [3, 10, 12].

Additionally, blending GNPs with biodiesel led to reduced ignition delay, lower emissions of UHC and CO, and increased BTE. It may be due to the addition of more oxygen by biodiesel, which converts more significant CO emissions into CO_2. Also, the rise in CP and temperature and the addition of oxygen molecules construct a vigorous atmosphere for combustion and charge oxidation.

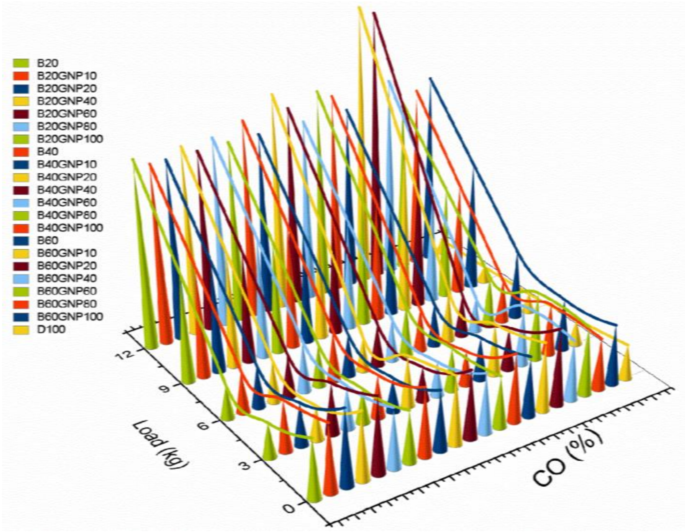


Figure 7. Impact of variable loads on CO emission for different fuel conditions

3.5 Carbon Dioxide (CO_2) Emissions

Figure 8 shows the influence of variable loads on CO_2 emission. It is higher in fuel mixture B20GNP20, B20GNP40, B40GNP40, B40GNP80, and B60GNP20 by 2.37 %, 2.31 %, and 1.97 % than the biodiesel B20, B40 and B60 due to the increase in oxygen for the total combustion of fuel in the engine. These findings show that the higher emissions of CO_2 for combination of nanoparticles with biodiesel at 3, 6, 9, and 12 kg of load. The increased CO_2 emissions at higher loads are related to the B20GNP20 blend. Moreover, the longer time for ignition allowed the charge for premixing with extra oxygen, and this helps in an increase in CO_2 emissions for the considered blends.

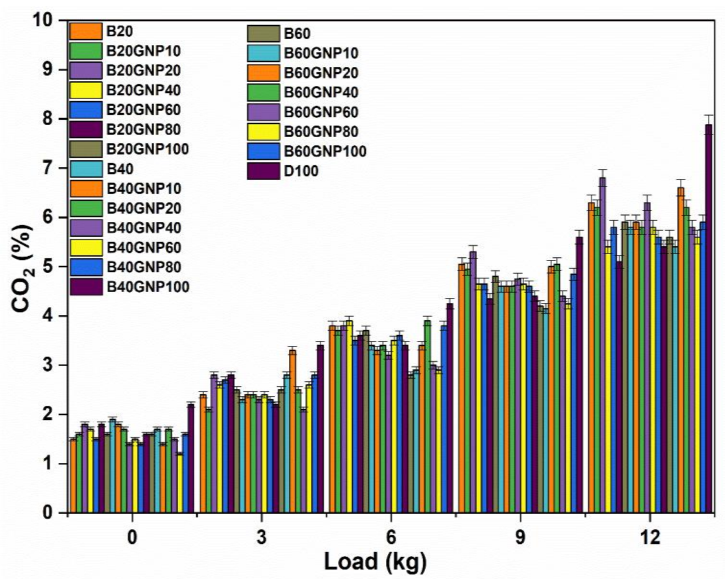


Figure 8. Impact of variable loads on CO_2 emission for different fuel conditions

3.6 Nitrogen Oxide (NOx) Emissions

Figure 9 illustrates the relationship between NOx emissions and varying loads for all the cases in comparison to pure diesel. NOx emissions are produced during combustion as a result of the interaction between oxygen and nitrogen gases in the air, particularly at higher temperatures. In densely populated cities with heavy motor vehicle traffic, the release of NOx significantly increases air pollution in the atmosphere.

The rate of NOx emissions is influenced by engine load and fuel type compared to other fuels. NOx emissions increase as the blending percentage increases at different loads in comparison to pure diesel. Compared to pure diesel, biodiesel mixed with GNPs maintained the lower temperature of the combustion chamber. For B20, B40, and B60 blends with and without GNPs found the rise in NOx by 4.86 %, 12.83 %, 17.81 %, and 14.83 %, 23.26 % and 35.86 %, respectively, compared to diesel at maximum load. Hence, the B40GNP100 fuel blend has lower NOx emissions at full (12 kg) load.

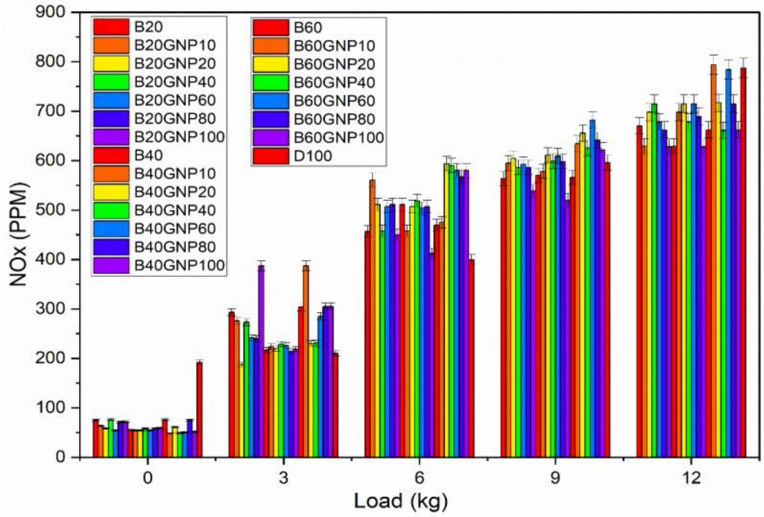


Figure 9. Impact of variable loads on NOx for different fuel conditions

3.7 ANN Results and Validation

In ANN for the present study, two performance parameters have been considered for training as input variables, i.e., BTE and BSFC of the engine. The ANN approach obtained overall regression coefficient for validation, training, and testing in the trained network is 0.9971, 0.99795, 0.99704 and 0.99259, respectively, see Figure 10. Along with the MSE values were 0.000341, 0.0009895, 0.000893 and 0.000159 for validation, training, overall and testing, respectively. Meanwhile, the MAPE value obtained from the considered model is 2.43 %. Figures 11 - 12 show the BTE and BSFC experimental results compared with the predicted result by ANN. In Figure 11 (a) and (b), Experimental and ANN predicted values of BTE are drawn, which shows the values obtained for R, MSE, and MAPE are 0.9999, 0.00092586, and 1.26 %, respectively. Similarly, Figure 12 (a) and (b) show the R, MSE, and MAPE values for actual and ANN-predicted BSFC, which are 0.99982, 0.00039492, and 1.45165 %, respectively.

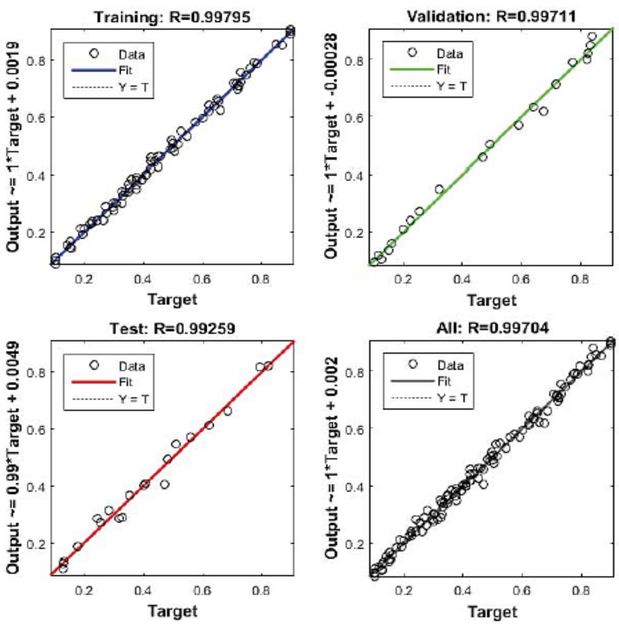
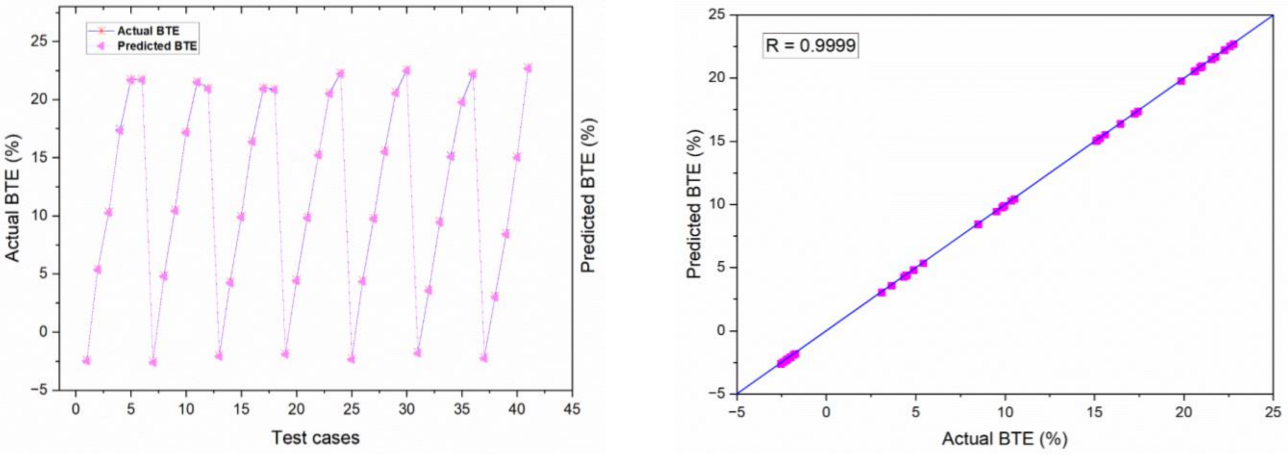
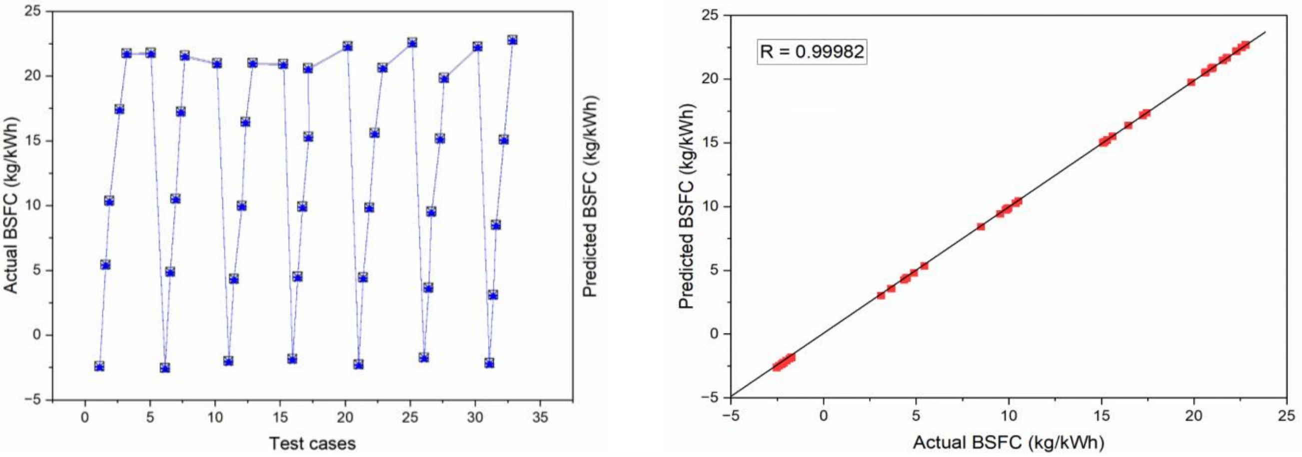


Figure 10. The overall R-value of the ANN model



(a) (b)

Figure 11. Comparative study of ANN predicted and actual BTE



(a) (b)

Figure 12. Comparative study of ANN Predicted and actual BSFC

3.8 Comparative Study

In this section, the highest BTE result of the B60GNP100 blend of the present work was equated with the findings of reported studies on bioethanol [6], jojoba biodiesel with 10% Al_2O_3 [16], rice bran biodiesel with CeO_2 [18], and soybean biodiesel [46], as shown in Figure 13. The results of the previous studies were only higher compared to the present study for BTE with variable load conditions. It was seen that the B60GNP100 blend yielded more promising results compared to the previous studies [6, 16, 18, 46], showing improvements of 2.46%, 11.34%, 15.69%, and 8.39%, respectively. This improvement is due to the increase in biodiesel surface area, resulting in a higher ignition delay and a rise in oxygen percentage in combustion, which facilitates the premixing of charges.

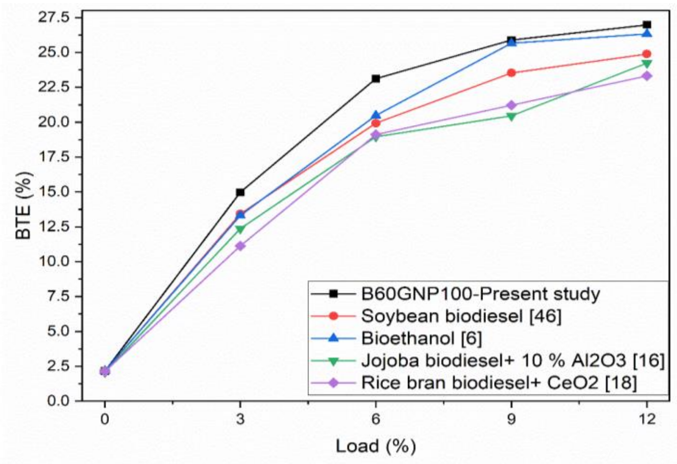


Figure 13. Comparative study with the reported works [6, 16, 18, 46] on biodiesel with and without nanoparticles

4. CONCLUSIONS

The outcomes of pure diesel and soybean biodiesel blends with and without the addition of GNPs for variable load conditions are discussed in the results section. After the threadbare results and discussion, the conclusions have been made as follows:

- The B60GNP100 blend under full (12 kg) load conditions demonstrates the highest brake thermal efficiency at 27.13 % compared to pure diesel.
- With an increase in load above 12 kg, the brake-specific fuel consumption is higher for diesel. At 6 kg to 9 kg of load condition it has the lowest brake-specific fuel consumption for the B40GNP80 blend compared to pure diesel.
- The emission percentage of biodiesel blends is in control compared to pure diesel, which shows that the blend considered with GNPs will have a significant role in compression ignition engine uses in the future.
- The ANN approach is a pioneer in optimization, which reduces the simulation time and provides accurate results at a low cost. Hence, the ANN model is more efficient for studying the IC engine applications.
- Overall Regression gives an optimized network at 0.99121, which shows an accurate relation between ANN predicted and experimental values, same as 0.000893, 3.1192 % for MSE and MAPE.
- The overall Regression coefficient for trained networks is 0.9999, which predicts the correctness of the actual and ANN predicted dataset, along with the MSE and MAPE, which are 0.0009895 and 2.43 %, respectively.
- The comparison of the B60GNP100 blend with previous studies [6, 16, 18, 46] indicates that the B60GNP100 blend achieves higher BTE by 2.46% [6], 11.34% [16], 15.69% [18], and 8.39% [46], respectively.
- In the future, the optimization of BTE and BSFC result data using the ANN model can be achieved, as the current results of this model align well with the experimental data.

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CONFLICT OF INTEREST

The authors have declared no conflict of interest.

AUTHORS CONTRIBUTION

P. M. Kadam- Formal analysis, methodology, validation, writing original draft, investigation;

D. R. Dolas- project administration and supervision;

S. Pal - Conceptualization, methodology, validation, visualization;

S. S. Gajghate - Investigation, conceptualization and writing original draft.

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