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Experimental investigation on CI engine fuelled with microalgae biodiesel and MgO nanoparticle

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Abstract: This study experimentally examines the influence of magnesium oxide nano-particulates on the performance and emission behaviour of a CI engine fuelled with microalgae biodiesel. MgO nanoparticles in proportions of 5, 10, and 15 ppm were dispersed into algal-diesel blend. The investigation was carried out at constant speed under various load conditions to evaluate the BTE, BSFC and exhaust emissions. The outcomes show that the addition of magnesium oxide enhances the combustion through effective catalytic oxidative reactions, improving air-fuel mixing and accelerating heat release. The BTE increased by 1.02%, while BSFC decrease by 2.81% compared with the diesel. Emission analysis showed a decrease in CO, HC, and smoke, whereasCO_2showed small rise due to improved oxidation of the fuel. A marginal increase in NOx emissions was observed at increased nanoparticle fractions, due to high peak combustion temperatures. The developed ANN model exhibited strong predictive capability with high R^2 values and proved effective in predicting engine performance and emission attributes. Overall, the findings indicate that microalgae biodiesel at an optimized concentration of MgO nanoparticles can improve CI engine efficiency, while simultaneously reducing the emissions.

Keywords: Microalgae biodiesel, Magnesium oxide nanoparticles, CI engine, Emission analysis, Artificial Neural Network.

1. Introduction

The increasing energy consumption and the continued usage of fossil fuels in transport and energy production have raised severe environmental and sustainability issues. Combustion of fossil fuels emits greenhouse gases and other types of harmful pollutants, which deteriorate the quality of air and have cause health and environmental impacts [1].Emissions, especially hydrocarbons, carbon monoxide, and nitrogen oxide, are a significant source of air quality degradation in the world[2]. Despite the outstanding efficiency, durability, and reliability of diesel engines, they produce high amounts of smoke and NOx, and thus, emission control remains a persistent problem[3]. Moreover, fuel shortage of fossil-based diesel and the issue of energy security have motivated researchers and industries to seek renewable and cleaner fuels. Biodiesel can serve as a renewable substitute for standard diesel because it possesses similar fuel characteristics, is renewable in nature, and offers environmental advantages. It can be generated from different sources, such as plant based oils[4], animal fats, microalgae, and used cooking oils, and making it a sustainable fuel choice[5]. Despite the wide availability of biodiesel feed stocks, their use in conventional diesel engines presents several limitations. These include reduced fuel efficiency due to lower calorific value, elevated cloud, pour points that cause cold-start problems, and increased fuel density, that results in poor atomization. Furthermore, it may contribute to corrosion of engine components, increased NO_x emissions, and piston ring sticking[6]. Blending biodiesel with diesel is an effective way to overcome these drawbacks without requiring major alterations to existing engines[7].Biodiesel is biodegradable and non-toxic, and it has no sulphur or other toxic compounds that are present in fossil fuels. It has a better combustion rate due to its natural oxygen content, resulting in a higher degree of fuel burning and reduced emissions compared with conventional diesel[8][9]. Biodiesel has some unique benefits such as a renewable, easily available, less environmentally harmful, and improved lubrication properties[10]. Its high oxygen concentration enables a higher degree of combustion, and can increase the overall engine efficiency. Biodiesel production is generally categorized into three generations depending on feed stocks. First generation biodiesel is obtained from food grade oils & animal fat, but it competes with food sources and raises sustainability concerns. Second-generation biodiesel is obtained from non-edible oils and waste, although the production process is relatively complex and yields are lower [11]. Third generation biodiesel is obtained from microalgae; which offers advantages such as high lipid content, fast growth, cultivation on non-arable land, and better CO_2fixation, making it more efficient and environmentally friendly option[12][13].Harvesting and drying algal biomass is the initial step in the production of microalgae biodiesel, which is subsequently extracted by using solvent extraction or mechanical pressing. The extracted oil is then subjected to an alkaline-catalysed transesterification process to methyl esters of fatty acid. The result in microalgae biodiesel possesses

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a greater cetane number, ensuring good ignition behaviours, smooth combustion, a high a flash point, and excellent lubricity, which contribute to safer handling and reduce engine wear. Furthermore, the low sulphur and aromatic content enable the fuel to generate lower exhaust emissions and improved engine performance [14]. Since biodiesel can be blended with diesel and can be deployed in existing engines without substantial changes, it is considered a viable and environmentally friendly solution for addressing emission concerns and the future energy demands[15]. However, despite promoting complete combustion, biodiesel blends may lead to lower efficiency and increased mass induction rate because of their higher viscosity, and diminished calorific values. Dispersion of nanoparticles into biodiesel blends has been identified as an effective strategy to control these issues[16]. Adding Nanoparticles into biodiesel mixtures demonstrably boost engine performance, and minimize emissions. Commonly used oxide nanoparticles are aluminium, titanium , zinc, copper ,cerium etc. [17][18][19].Their elevated surface area-to-volume ratio and catalytic attributes enhance fuel atomization, increase droplet evaporation, minimize ignition delay, and support uniform air-to-fuel mixing, resulting in more complete combustion[20]. Among these, metal-oxide nanoparticles are particularly effective, as illustrated in Figure.1, due to their ability to provide oxygen-rich active sites for oxidation of hydrocarbons, carbon monoxide, and smoke. They also enhance thermal conductivity for efficient heat transfer; reduce localised hot spots, and minimise thermal stresses on engine components. Their catalytic action ensures stable flame propagation, increased combustion

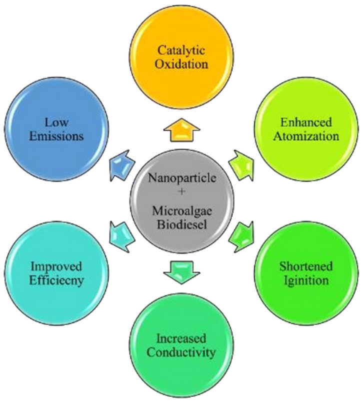


Fig. 1. Merits of Nanoparticles with Biodiesel

efficiency, higher BTE, and reduced BSFC. Although a moderate rise in nitrogen oxides (NOx) may occur due to elevating local temperatures, the overall effect includes cleaner emissions, more stable combustion, better energy utilization, and superior thermal performance, making metal-oxide nanoparticles highly suitable for sustainable biodiesel engine applications [21][22].Among various nanoparticles, magnesium oxide nano additives are considered particularly demonstrating due to their strong catalytic characteristics and high thermal stability. They improve fuel-air mixing, improve atomization, facilitate efficient combustion, reduce emissions[23]. Kunchi et al.[24] have examined the effects of zinc and manganese co-doping on bismuth ferrite (BZnFMO) nanoparticle in Baheda biodiesel blends containing 50-75 ppm with varying injection timings. The incorporation of BZnFMO nanoparticles improved the burning properties such as cylinder pressure, heat discharge rate and BTE, while reducing BSFC, CO, HC, smoke emissions, with a slight rise in NOx at advanced injection timings. Ansari et al.[25]studied the role of aluminium oxide (Al_2O_3) n in a JB30-diesel blend in CI engine. Al_2O_3 nanoparticles were added at 50 ppm, resulted in improved BTE, reduced BSFC, lower combustion pressure& reduced noise emissions. The ternary blend DF67JB30Al_2O_3 performed better than the binary DF70JB30 blend. Similarly, K. Simhadriet al.[26]evaluated the role of titanium oxide nano-additives on Mahua B20 blend in compression ignition engine under different injection pressures (180-240 bar). TiO_2 was added at concentrations of 25, 50, 75, and 100 ppm. The findings indicated the inclusion of nanoparticles enhanced BTE, reduced BSFC, particularly under elevated injection pressures. Augmented ignition metrics were identified at decreased injection pressure, where the biodiesel with titanium oxide with 50 ppm blend recorded higher cylinder pressure values comparable to diesel fuel with a 5.3% high HRR. Additionally, CO, HC emissions were reduced, whereas carbon dioxide emissions showed a slight increase. Alehegn et al.[27]evaluated the influences of Al_2O_3NP (100 ppm) in Millettiaferruginea biodiesel blends (B10-B30) in CI engine, observing improved BTE, reduced BSFC, promoted combustion, and decreased CO, HC, EGT and NOx emissions, especially at B30belnd.Mujtaba et al. [28]assessed the role of oxygenated alcohols, nano dopants toward lubricity of diesel-palm-sesame B30 fuel through the HFRR along with SEM. Traditional B10 diesel and ethanol-mixed B30 exhibited low lubricity & improved wear and friction, whereas dimethyl carbonate (DMC)-mixed B30 interfered with the wear scar diameter, enhancing performance and emissions. TiO_2 nanoparticles produced the best friction coefficient and wear scar, providing improved engine performance and lubricity. Nachippan et al.[29]reported that MgO nanoparticles (70 ppm) in cottonseed biodiesel B30 in a CI engine and noted elevated BTE, decline in BSFC, carbon monoxide, hydrocarbons, NOx, and smoke emissions through better combustion. Economic and life cycle analyses have confirmed that nano-MgO-doped cottonseed biodiesel can be considered a good sustainable fuel, even with a high cost of additives .Muni Mathan et al.[30] studied the application of CeO_2 nanoparticles at a portion of 0.5% in tobacco seed oil (TSOB) B40 mixtures in CI engines. The inclusion of CeO_2 nanoparticles enhanced combustion behaviours by increasing in-cylinder pressure, HRR, resulting in BTE of 29.2% and a BSFC 0.21 kg/kWh. Significant reductions were also recorded, with CO, HC & particulates reducing by 20%, 25%, 15%. Although a slight rise NOx was noted. From above literature, CeO_2 nanoparticles increase combustion through their oxygen storage-release capability, while Al_2O_3 improves heat transfer due to its high thermal conductivity. However, CeO_2 is relatively expensive and aluminium oxide may lead to injector wear due to its hardness. In comparison, MgO exhibit good catalytic activity and high thermal stability, and better availability at lower cost.

2. Materials and Methods

2.1 Preparation of Microalgae biodiesel

Microalgae are single-celled photosynthetic organisms that can be found in freshwater, saltwater, and wastewater and can build up a large lipid content that can be used to produce biofuel. They are found naturally in water bodies and may be cultured under controlled conditions in open raceway ponds or closed photo bioreactors with sunlight, carbon dioxide, water and necessary nutrients. Due to the high rate of growth, large oil production per unit area, and the absence of competition with food sources, microalgae have become an effective raw material for generating biodiesel. Table 1. Lists out the various properties of biodiesel. In this study, the microalgae strain Chlorella vulgaris, which typically contains 30-45%oil content, was selected for biodiesel production and grown in a nutrient-based medium under controlled light intensity, temperature, and aeration for about 10-15 days to induce lipid deposition. Centrifugation or flotation method is employed for harvesting the obtained biomass after cultivation, which is dried in the heating chamber at 60-70˚C until moisture content is completely removed. An organic solvent extraction process was employed to obtain the lipids; dried algal biomass is immersed in solvents like n-hexane or a mixture of chloroform and methanol to break up the cell structures and dissolve the intracellular oils. The extraction process usually lasts 4-6 hours with constant stirring. After recovery of the solvent through evaporation, crude microalgae oil is recovered. This is then converted into biodiesel using a process called transesterification in the presence of a base catalyst, where methanol reacts with the triglycerides in the presence of a catalyst of sodium hydroxide at a molar ratio of 6:1 (CH_3OH: lipid). This reaction is carried out at a temperature of 60-65 °C for 60-90 min to give fatty acid methyl esters and glycerol. The FAME composition of microalgae biodiesel primarily consists of saturated and unsaturated fatty segments such as hexadecenoic, octadecenoic, and octadecadienoic acids and analysed according to the standard method ASTM D6584[31].The resulting biodiesel is permitted to settle, then separated, washed, and dried to get refined microalgae methyl ester to be used for further experimental purposes. A B20 fuel blend was synthesized by combining 20% microalgae-derived biodiesel with 80% conventional base fuel, prepared on a volumetric basis.

Table1. Properties of Microalgae Biodiesel.

Property	Typical Value
Density (kg/m^3)	880
Kinematic Viscosity@ 40˚C	4.6
Flash and Fire Points (˚C)	145&175
CV (MJ/kg)	38.5
Pour point and cloud point (˚C)	5 &-2

2.2 MgO Nanoparticle

Magnesium oxide is a lightweight ceramic nanoparticle that has high thermal conductivity as well as catalytic properties and thus is an effective additive to biodiesel. It has a large surface area, causing the fuel to burn faster and cleaner as it enhances oxidation and dissociation of the heavier molecules during combustion. For this study, MgO-biodiesel was prepared by adding 5 ppm, 10 ppm, and 15 ppm of magnesium oxide nanoparticles to 1000 ml of microalgae biodiesel. Initially, magnetic stirring facilitated the dispersion of nanoparticles for preliminary mixing. Subsequently, the blends were subjected to ultrasonication using a Prescientific ultrasonicator to break nanoparticle agglomerates and obtain uniform dispersion. Ultrasonic agitation was carried out for approximately four hours at 200 rpm and 60 Hz, with an effective exposure time of 80 minutes per cycle, and the procedure was repeated three times to enhance reliability. A small quantity of Sodium dodecyl sulphate was incorporated into surfactant to minimize the surface tension and prevent aggregation. The combined effects of magnetic stirring, ultrasonication, and surfactant addition improved nanoparticle dispersion and helped minimize particle sedimentation and increasing emulsion formation in the fuel blend. The prepared nano fuel blends were visually inspected for sedimentation prior to the engine experiments to ensure stable dispersion. Proper stability is necessary for injector applications because poor dispersion can lead to the injector blockage in engine applications; extended sonification effectively stopped nanoparticles from clumping together and kept the combination stable. Table 2lists the characteristics MgO nanoparticles.

Table 2. Characteristics of MgO nanoparticle

Characteristics	Value
Chemical Symbol	MgO
Batch	Mg-2, O-16
Chemical Composition	MgO (60.29%), O_2 (39.67%)
Colour	White
Size	5–100 nm
Molar Mass	40.30 (g/mol)
Density	3.58 (kg/m^3)
melting point	2852˚C
boiling Point	3600˚C

2.3 Experimental Procedure

Single-cylinder 4-stroke, water cooled compression ignition engine manufactured by Kirloskar was employed for the experimental investigations, running at fixed speed at 1500 rpm. It has a 110 mm stroke length, 87.5mm bore diameter, and a static compression ratio of 17.5:1. An eddy current dynamometer was used to gradually raise the engine load from idle to its peak load, as illustrated in Figure 2.

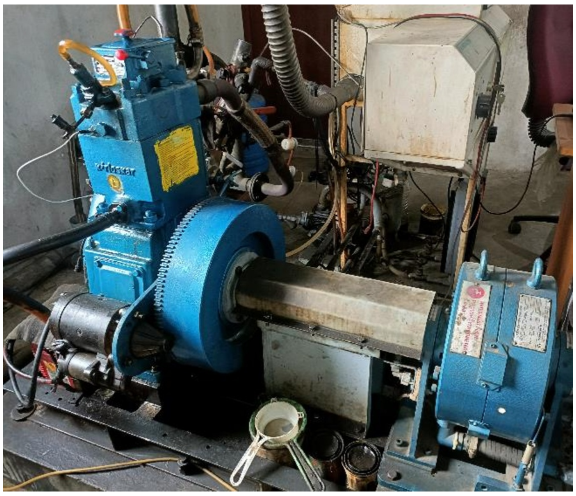


Fig. 2. View of experimental set up.

The test fuels included neat diesel (D100), microalgae biodiesel (B20D80), and microalgae biodiesel mixed with nanoparticle additives with 5, 10 and 15 ppm. Exhaust emissions were determined through the Five gas analyser (AVL DI GAS 444 N), specifications are presented in Table 3, & smoke emission levels were recorded through AVL 437C smoke meter. Cylinder pressure measurement was done with a piezoelectric pressure transducer for combustion study. All experiments were conducted 3 times under uniform conditions, the mean values are reported. The standard deviation is illustrated using error bars on the graphs.

Table 3. Specification and Operational Range of AVL DI GAS 444 N

Parameter	Detection Span	Detection Sensitivity	Precision
Carbon monoxide	0-15% by volume	0.01% volume	±0.02%(abs) ; ±3%(rel)
Carbon Dioxide	0-20% by volume	0.01% volume	±0.3% vol(abs), ±3%(rel)

Hydrocarbons	0-30,000 ppm	1 ppm ≤ 2000 10 ppm> 2000	±8 ppm(abs); ±3-10(rel)
Nitrogen Oxide	0-5,000 ppm	1 ppm	±5 ppm(abs); ±1%(rel)
Engine Speed	400-6000 rpm	1 rpm	±1% (relative)

3. Results and Discussion

3.1 Brake Thermal Efficiency

Figure 3, demonstrates the change in BTE across engine load for diesel baseline, microalgae fuel blend (B20D80) with 5, 10, and 15 ppm of MgO nanoparticles. It has been observed that the brake thermal efficiency (BTE) increases with increasing engine load for all the blends, indicating better combustion and utilization of energy content in the fuel. All nanoparticle-doped blends have larger BTE in the whole load range than D100, which is evidence of improved combustion properties. The improvement at part and medium loads (25-50%) stems from its excellent catalytic properties, superior heat conduction of MgO, which enhance finer atomization, increase the rate of evaporation and enhance the blending of fuel and air that allows further full combustion to occur. The B20D80 + 15 ppm MgO blend has the largest BTE (75-100%), due to an increased oxidation process, better flame propagation and decreased heat losses. In general, the findings confirm the fact that the addition of MgO nanoparticles, especially 15 ppm, can considerably increase the thermal efficiency of the microalgae biodiesel blends enhanced 1.02% BTE in relation to diesel and thus have a high potential to be used as efficient and sustainable alternatives to traditional diesel fuel.

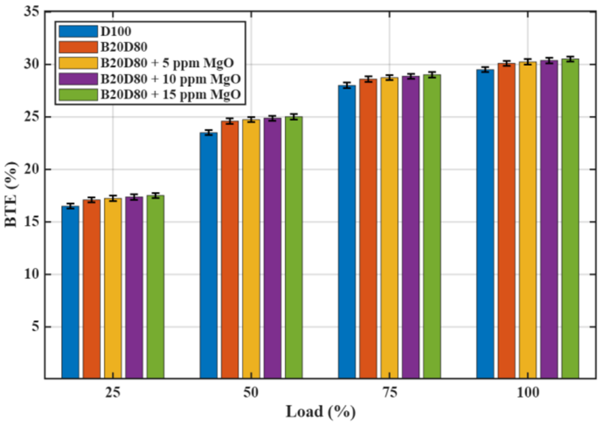


Fig. 3. BTE vs Load for Tested Fuels

3.2 Brake Specific Fuel Consumption

Figure 4 showcases the trends of bsfc versus load when using diesel (D100) & microalgae biodiesel blend (B20D80) with MgO nanoparticles of concentrations of 5, 10, and 15 ppm. BSFC of all evaluated fuels indicates the decreasing tendency as engine load rises, due to the fuel is burned more efficiently, heat losses are reduced, & utilization of fuel energy is improved.

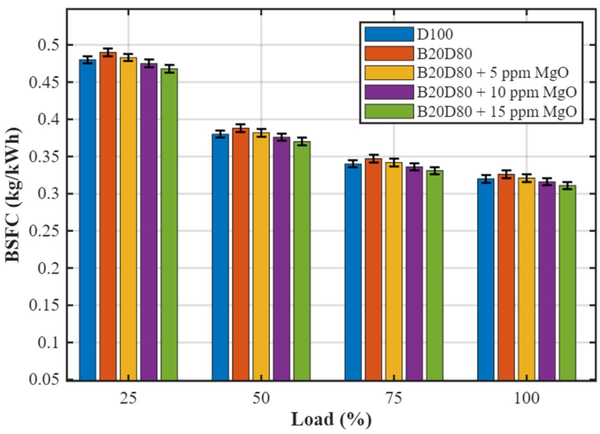


Fig. 4. BSFC vs Load for Tested Fuels.

The blends enriched with nanoparticles show relatively lower BSFC under all loads relative to D100, which strongly suggests the better fuel economy. In contrast with B20D80, the integration of magnesium oxide nano-additives further decreases BSFC due to improved combustion. It is predominantly that the BSFC is reduced at lower and intermediate loading conditions due to enhanced fuel dispersion, increased vaporization rate, enhanced air-fuel mixing facilitated by catalytic activity, thermal conductivity (MgO nanoparticles). With high-load, the combination of B20D80 + 15 ppm of MgO is the lowest BSFC. Showing a 2.81% reduction over diesel, due to increased oxidation reactions, better flame growth, and complete combustion, resulting in decrease in fuel fraction. In general, these findings validate the hypothesis that inclusion of magnesium oxide, especially with the optimal dosage at 15 ppm, can greatly enhance the fuel economy of microalgae biodiesel blends, making them a promising alternative to conventional diesel fuel.

3.3. Emissions

3.3.1 Hydrocarbons:

Effect of engine load on unburned HC emissions of neat diesel (D100), B20D80with addition of 5, 10, and 15 ppm of MgO nanoparticles is examined. All the tested fuels show a gradual decline in HC with rising load, primarily owing to their elevated cylinder temperature and increased oxidation of hydrocarbon species. Compared to diesel, the microalgae biodiesel shows a relatively low HC emissions due to inherent oxygen. Furthermore, when the nanoparticle-doped biodiesel blends have significantly reduced the HC in relation to diesel, and B20D80 as observed inFigure5. The observed decrease in HC emissions is mainly ascribed to the natural oxygen concentration inside microalgae biodiesel and the catalytic behaviours of MgO, which enhance finer fuel dispersion, accelerated evaporation and enhanced air-fuel mixing. Among the tested blends, B20D80 + 15 ppm MgO achieved lower hydrocarbon emissions across the load, which recorded a 3.4% reduction compared to diesel. Overall, the results confirm that the influence from both the biodiesel oxygenation and the addition of MgO nanoparticles are effective in reducing the unburnt hydrocarbon emission.

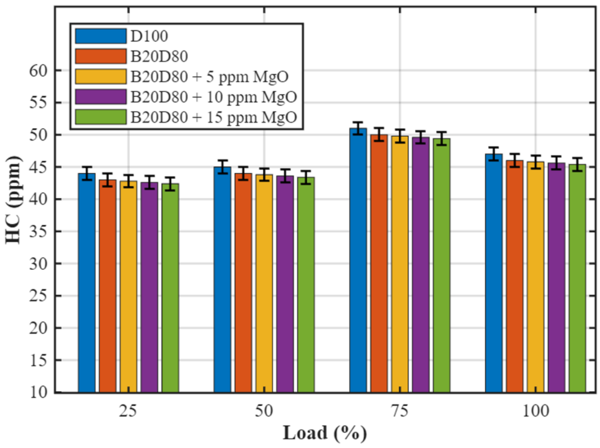


Fig. 5. HC Vs Load for tested Fuels.

3.3.2 Carbon Monoxide:

CO emissions decrease with escalating load for every fuel blend prompted by enhanced flame temperature inside the cylinder and oxidation reactions, as shown in Figure 6. Neat diesel (D100) exhibits higher CO emissions than B20D80 and MgO-blended fuels, and this implies incomplete combustion. The B20D80 mix has less CO than diesel, stemming from inherent oxygeneration, which facilitates full combustion.

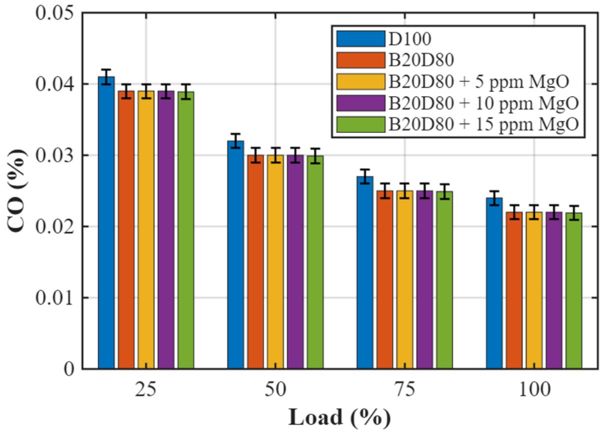


Fig. 6. CO Vs Load for tested Fuels.

Moreover, MgO nanoparticles addition significantly decreases the CO emissions across all load conditions in comparison with B20D80. Among tested fuels, B20D80 + 15 ppm MgO exhibits the lowest CO emission. At maximum load, CO values of diesel, B20D80 + 15 ppm MgO are 0.024 and 0.0219, respectively which represents a reduction of approximately 8.75%. This reduction can be caused by enhanced catalytic oxidation impact in MgO, increased air-fuel mixing, as well as high combustion efficiency, which validates the superiority of MgO-doped microalgae biodiesel blends with respect to the environment.

3.3.3 Smoke:

Smoke emission gradually decreases with increasing load for all fuels, as demonstrated in Figure 7, because of higher cylinder temperature and enhanced oxidation reaction. However, the B20D80 blend reveals a minor rise in soot at full load relative to neat diesel (D100), owing to its relatively high viscosity, poor spray atomization properties. Compared to the B20D80, the addition of MgO nanoparticle with B20D80 significantly decreases smoke emissions at all loads. In particular, the B20D80+15 ppm MgO shows a substantial reduction in smoke emission, observed a 3.03% decrease in relation to diesel operation at high load. This reduction results from catalytic oxidation performance by MgO nanoparticles, increased micro-atomization of fuel droplets, augmented fuel air homogenization, quicker oxidation of soot precursors, leading to lower emissions and more efficient combustion. Overall, the B20D80 + 15 ppm MgO, blend consistently exhibits the lowest smoke emissions, demonstrating its superior performance and environmental benefits.

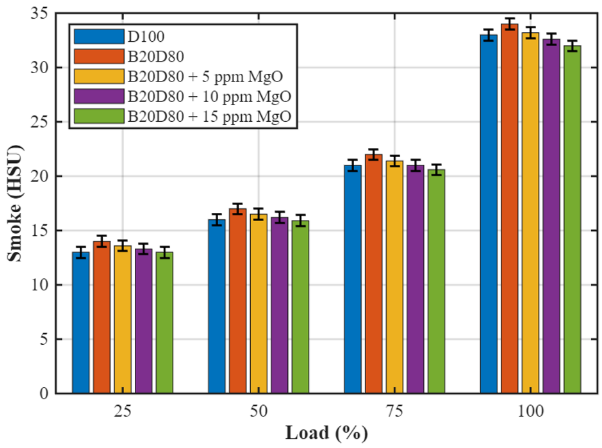


Fig. 7. Smoke Vs Load for tested Fuels.

3.3.4 Nitrogen Oxide

Figure 8 presents the relation between NOx emissions and load. Neat diesel (D100) has the lowest NOx emissions throughout the entire load range due to its relatively low fraction of oxygen and moderate peak combustion temperature. The B20D80 blend exhibits a slight change in the nitrogen oxide emission relative to D100 due to the oxygenated nature inside the biofuel, which catalyses the combustion efficiency, alongside slight rise in cylinder temperature. Moreover, the addition of MgO to the B20D80 mix leads to a moderate rise in NOx. It increases moderately in comparison with B20D80 due to the fast combustion rate. Among all tested blends, the B20D80 + 15 ppm MgO blend exhibits the highest NOx by 9.92% than diesel, which is primarily due to better fuel-air mixing, higher catalytic action, faster combustion kinetics, and a slight increase in combustion temperature in cylinder. However, this NOX trade-off can be mitigated by using exhaust gas recirculation and water injection. EGR lowers the oxygen concentration and peak combustion temperature, while water injection accumulates heat throughout vaporization, decreasing flame temperature, thereby limiting NOx generation.

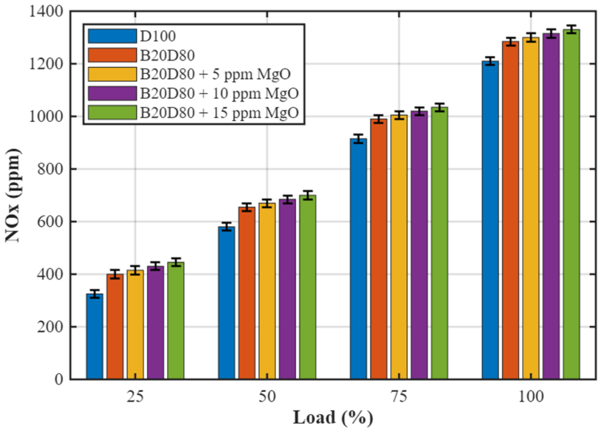


Fig. 8. NOx Vs load for tested fuels.

3.3.5 Carbon Dioxide

The influence of loading on CO_2emissions for various blends is illustrated in Figure 9, such as D100, B20D80 and MgO nanoparticle-blended fuels, which is mainly because of higher combustion efficiency at higher loads. Neat diesel (D100) exhibits relatively low CO_2 emissions across all load conditions, and biodiesel blends shows slightly higher carbon dioxide levels owing to the oxygen available in methyl ester, driving efficient thermal release. B20D80blend has a moderate rise in CO_2 levels compare with diesel. Furthermore, the introduction of MgO nanoparticles (5 ppm, 10 ppm and 15 ppm) to the B20D80results further increase in CO_2 levels compare with B20D80. Among all tested fuels, the B20D80 + 15 ppm MgO blend records the highest carbon dioxide emissions across the load range, due to the catalytic action of MgO leading to enhanced efficiency, oxidation of carbon and better oxidation of the fuel within the engine cylinder.

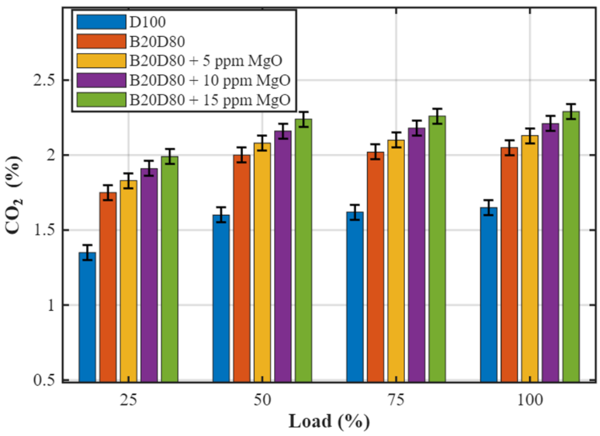


Fig. 9. CO_2 Vs Load for tested blends.

3.4 Combustion Characteristics

The changes in pressure inside the cylinder and HRR correlated with crank rotation for all fuels, as illustrated in Figures 10&11; biodiesel with MgO nanoparticles demonstrates a higher level of combustion than the pure diesel. Based on the HRR plot, diesel has the lowest peak heat release rate of approximately 100 kJ/CA at the crank angle of about 360˚, whereas B20D80 + 15 ppm MgO has a higher peak heat release rate, with the highest HRR around 116 kJ/CA, which is a sign of more intense and faster premixed combustion relative to diesel.

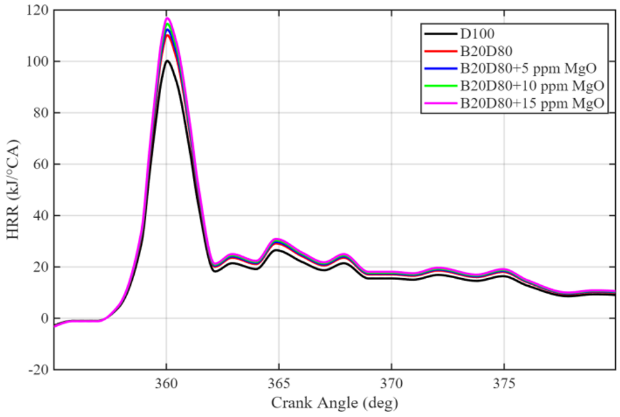


Fig. 10. HRR Vs Crank Angle for various blends.

Similarly, the cylinder pressure plot indicates that diesel attains a low peak pressure of 65 bar, while MgO dispersed blends, particularly B20D80 + 15 ppm MgO, achieve higher cylinder pressure of 73 bar with, which is considerably greater than base fuel, due to enhanced combustion behaviour, better oxidation reactions and better heat release behaviour, and catalytic activity of MgO. It causes better combustion and enhances engine performance in relation to diesel operation. The High HRR values showed improved combustion intensity and energy discharge in premixed combustion stage. The HRR integral represents the cumulative heat energy released in the cylinder, reflecting enhanced fuel energy utilization for MgO nanoparticle blended fuels compared to diesel.

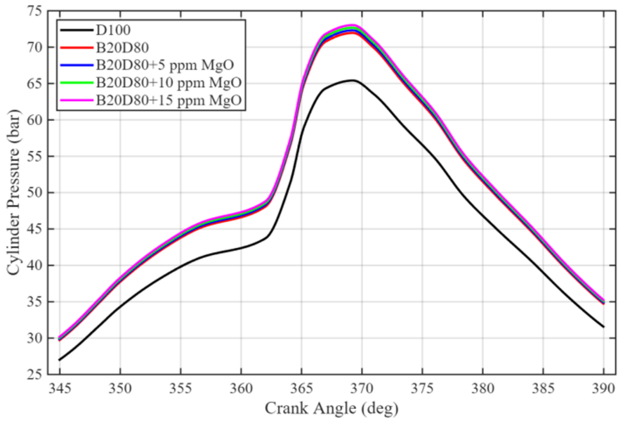
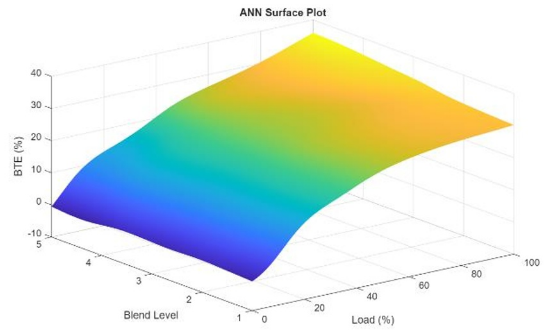


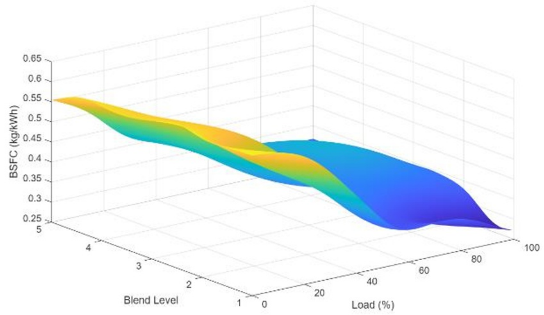
Fig. 11. Progression of In-cylinder pressure vs. Crank Position for fuel combinations.

4. ANN Analysis

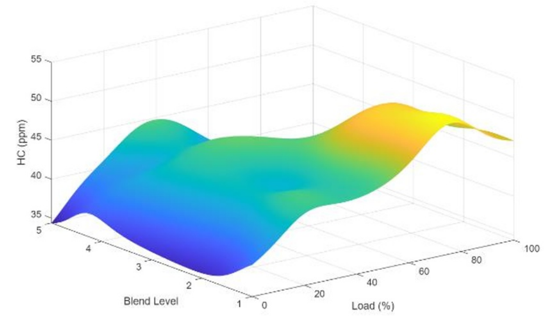
Artificial Neural Network model was used in predicting and optimizing engine behaviour and emission features based on experiment results[32]. Engine load and blend ratio was selected independent factor, while engine efficiency metrics (BTE, BSFC) and emission constituents (CO, HC, CO_2, smoke, & NOx) was considered as dependent variables. The ANN model followed a 2-10-7 architecture consisting of two input neurons, ten neurons in one hidden layer along with7 output neurons. The data was split into 70 percent and 30 percent training and validation to guarantee the development of the model in a reliable manner and minimal overfitting. ANN was tested on the basis R-squared value, the obtained coefficients are BTE=0.97, BSFC=0.92, hydrocarbons=0.90, carbon monoxide=0.99, Smoke=0.85, Nox=0.96, and CO_2 =0.82, indicating a high degree of consistency between the outcomes of the experiment and the prediction. The visual representation of effect of independent factors upon output responses and identification the optimal operating regions was made by response surface plots obtained using the ANN model, as illustrated in Figure 12. The uniform and smooth patterns of the surface predict characteristics of a stable ANN and prove that it is effective in analysing and optimizing engine performance over the established operating range a


ANN Surface Plot
BTE (%)
40
30
20
10
0
-10
5
4
3
2
1
Blend Level
0
20
40
60
80
100
Load (%)

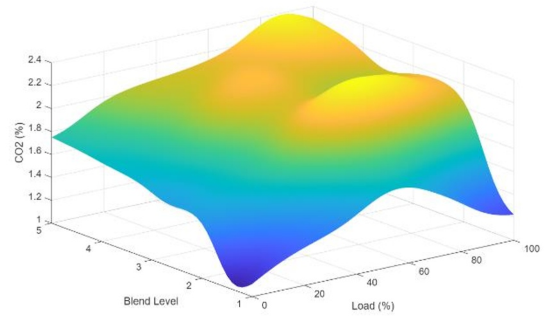
b


BSFC (kg/kWh)
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
5
4
3
2
1
Blend Level
0
20
40
60
80
100
Load (%)

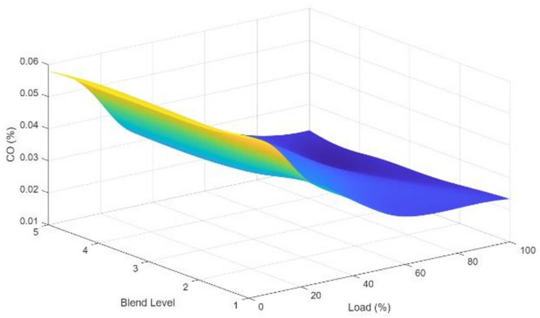
c


HC (ppm)
55
50
45
40
35
5
4
3
2
1
Blend Level
0
20
40
60
80
100
Load (%)

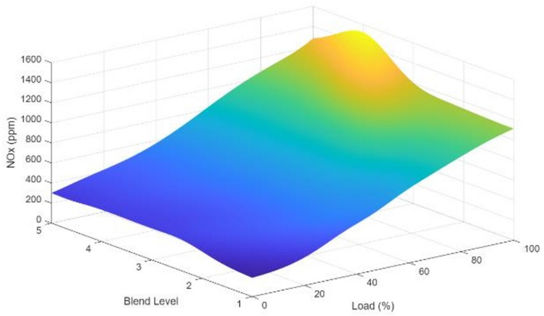
d


CO2 (%)
2.4
2.2
2
1.8
1.6
1.4
1.2
1
5
4
3
2
1
Blend Level
0
20
40
60
80
100
Load (%)

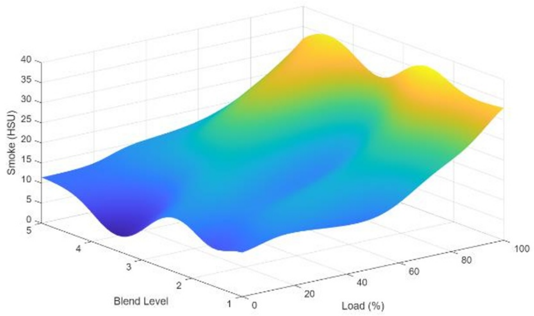
e



f



g



h

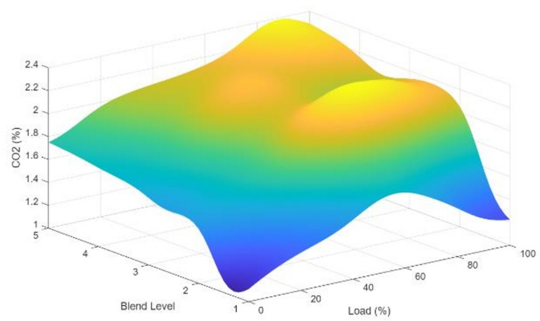


Fig. 12. Surface plots associated with performance of engine and emission variables.

Conclusion

Current experiment assessed the performance, emissions, and combustion peculiarities of a CI engine operated through MgO nanoparticle-blended microalgae biodiesel under different load conditions, along with ANN-based predictive modelling. The obtained results indicated the blend B20D80+ 15 ppm MgO exhibited superior performance, emission behaviour. BTE increased by 1.02% reliant on diesel, while the BSFC decreased by2.81%, relation to diesel, indicating improved fuel utilization. Emission analysis indicated that HC and CO decreased by 3.4% and 8.75%. In addition, smoke opacity was decreased by 3.03%, which can be resulting from better oxidation and enhanced combustion caused by the catalytic activity of MgO nanoparticles. Combustion analysis further showed an improvement in pressure inside the cylinder and a higher heat release, demonstrating enhanced combustion efficiency, rapid heat release within the cylinder. Moreover, the developed ANN model exhibited strong predictive capability and proved to be an effective tool for modelling nonlinear behaviour of the CI engine operating with nanoparticle-blended biodiesel fuels. The experimental findings indicate the incorporation of MgO nanoparticle into Microalgae biodiesel improves engine efficiency, promotes more complete fuel combustion characteristics and decrease exhaust emissions, making it a promising approach for improving CI engine operation.

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