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# Investigating the Effects of Nanoparticle Based Borax Decahydrate as a Fuel Additive in Blending Spirulina Biodiesel with Diesel Fuel for Emission Control in a 4-stroke Diesel Engine

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## Abstract

In recent years, the efforts to enhance engine efficiency have intensified due to the increased fuel consumption resulting from a growing number of cars on the roads. The rise in emissions has led to stringent regulations for diesel engines, although they are still commonly used, especially in freight transportation. Extensive research has been conducted by manufacturers and academics to address the emission issues associated with diesel engines. One approach to reduce emissions involves blending nanomaterials with diesel fuel; however, there has been limited exploration of blending biodiesel with diesel fuel. This study sought to examine the effects of incorporating borax decahydrate as a fuel additive into a 4-stroke diesel engine, specifically by blending Spirulina biodiesel with diesel fuel. To achieve this, borax decahydrate was meticulously dissolved in the biodiesel and varying amounts of biodiesel (1g, 3g, 5g, 7g, and 10%) were added to diesel. Five different fuel blends were examined: 90% diesel + 10% Spirulina biodiesel (S10), 90% Diesel + 10% Spirulina biodiesel + 1 g borax decahydrate (SB10B1), 90% diesel + 10% Spirulina biodiesel + 3 g borax decahydrate (SB10B3), 90% diesel + 10% Spirulina biodiesel + 5% g borax decahydrate (SB10B5), and 90% diesel + 10% Spirulina biodiesel + 7% g borax decahydrate (SB10B7). Among the fuel blends tested, SB10B3 exhibited improved brake thermal efficiency compared to diesel. This was attributed to proper combustion and early fuel injection. Additionally, SB10B3 demonstrated lower BSFC (Brake specific fuel consumption) than diesel across all load conditions, making it the optimal blend based on fuel efficiency. The metallic nanoparticle-enhanced samples displayed reduced levels of CO (Carbon monoxide) and $CO_2$ (Carbon dioxide) compared to diesel fuel under all loading conditions, owing to their higher oxygen content (8% to 9% more than diesel) facilitating better combustion. Notably, SB10B3 exhibited the lowest CO emissions among all the fuel blends. The nanoparticle-enhanced samples displayed reduced levels of CO and $CO_2$ compared to diesel fuel under all loading conditions, owing to their higher oxygen content (8% to 9% more than diesel) facilitating better combustion. Notably, SB10B3 exhibited the lowest carbon monoxide emissions among all the fuel blends.

## Keywords

Spirulina biodiesel, Diesel, Borax decahydrate, CI engine, Emissions

## Introduction

As the world's population expands and living standards improve, the demand for energy experiences a parallel growth. To address this escalating need for energy, there has been a notable increase in the utilization of fossil fuels. Unfortunately, this surge in fossil fuel consumption has exacerbated the problem of fossil fuel depletion and has resulted in a significant hike in their prices [1]. The

need to look into alternative fuels like biofuels is vital because fossil fuel sources are rapidly depleting. Since it takes years to generate fossil fuels like crude oil, their supply will likely run out shortly at the current rate of exploitation [2]. Moreover, the utilization of fossil fuels has detrimental environmental consequences, including the escalation of greenhouse gas emissions, depletion of the ozone layer, acid rain formation, deforestation, and water pollution through eutrophication. Consequently, there is an urgent need to explore affordable, sustainable, and easily accessible renewable energy alternatives. Biodiesel and alcohols have garnered significant attention as potential substitutes for diesel fuel due to their capacity to reduce both fuel consumption and pollution emissions. The best method to address the world's energy needs is with renewable energy sources because of their vast potential and abundance [3]. In recent times, the importance of biodiesel fuel has escalated significantly as it exhibits the potential to replace petroleum-based derivatives, which are projected to be depleted within the next century. Biodiesel fuel is gaining traction due to its environmental advantages over fossil fuels, leading to its increased usage as a means to mitigate harmful emissions. The fuel made from the oil called biodiesel is made up of several mono-alkyl esters. This fuel has less CO and HC (Hydrocarbon) emissions since the carbon is permanently trapped in the exhaust [4-6].

Furthermore, using biodiesel reduces the effect of greenhouse gases because it does not cause an increase in atmospheric $CO_2$. The need for vehicles is rising daily due to the growing world population, the advancement of technology, and the rising standard of living. Due to the strict emission rules, studies to lower engine emissions and the number of automobiles has grown. The search for more affordable or environmentally friendly gasoline is progressing daily. In this regard, research on incorporating metallic nanoparticles into diesel fuel is ongoing [7-10]. The metallic nanoparticles are known to improve combustion efficiency and lower emission levels. Size of nanoparticles typically range from 1 to 100 nm. In literature, different oxides of metals such as copper oxides, $Al_2O_3$ (Aluminum oxide), $CeO_2$, $Fe_2O_3$ (Iron oxide), $Fe_3O_4$, $TiO_2$, and ZnO (Zinc oxide) are employed as additives for diesel engines [11].

Various metals, including magnesium, silver, copper, as well as semi-metals like boron, find applications in various industries [12-13]. Extensive research has been conducted by numerous scholars to explore diverse biodiesel blends and the incorporation of metallic nanoparticles into diesel fuel. These investigations primarily focus on examining combustion processes, performance attributes, and emission profiles [14-15]. The experimental work by adding three different compositions of iron oxide with three different blends of *Pongamia pinnatta* biodiesel to diesel fuel in an engine running under four other loads and found the results. Optimal engine performance has been observed with a mixture comprising 20% blended *P. pinnata* biodiesel in conjunction with diesel fuel. Furthermore, the inclusion of metallic nanoparticles has demonstrated enhanced engine performance characteristics while effectively reducing emission pollutants. Kamesh [16] conducted experiments on a diesel engine, exploring different injection pressures and incorporating varying concentrations of metallic nanoparticles into the diesel fuel.

Specifically, they tested combinations of 80 and 100 ppm ZnO, 80 and 100 ppm $Al_2O_3$, and 100 and 200 ppm $Fe_2O_3$ comparing them to diesel fuel. Among the tested metallic nanoparticles, ZnO showed the most substantial reduction in CO and HC emissions. However, it is worth noting that all nanoparticles led to an increase in $CO_2$ emissions. Seela et al. [17] conducted experiments involving the addition of ZnO at two varying compositions and biodiesel derived from Mahua oil at three different compositions to diesel fuel at five distinct load scenarios. The generalized regression neural network has been used to estimate experimental data. The best mixture for biodiesel is 20% biodiesel added to diesel fuel and adding 50 ppm ZnO has enhanced engine performance and emission characteristics. Additionally, they recommended using the generalized regression neural network model estimate in future research because it closely matches the outcomes of experiments.

Reddy et al. [18] suggested that *Schizochytrium* microalgae oil-based biodiesel can replace traditional diesel fuel in DI engines. The study focused on investigating the combustion, performance, and emission metrices of microalgae biodiesel and its blends when utilized in 1-cylinder diesel engines. It was discovered that the properties of biodiesel complied with ASTM specifications. Biodiesel engines were permitted due to evidence that they were as efficient and effective as those powered by fossil fuels.

Haik et al. [19] experimented on methyl ester of algal oil and raw algal oil evaluated in a diesel engine. Parameters and heat dissipation were all studied. Methyl ester of algal oil has successfully developed the power from diesel vehicles due to its resemblance to diesel fuel. However, it increased combustion noise and decreased the engine's output torque slightly. To increase engine power and reduce combustion noise, some engine design elements, such as the CR and fuel injection timing, can be adjusted. Ospina et al. [20] found that combining biodiesel derived from algae with diesel fuel is likely possible to overcome the use of diesel fuel while maintaining the engine's performance. Performance, emissions, and engine roughness are the three main concerns of the automotive industry. Three different biofuels and standard diesel were compared in studies using the single cylinder DI Ricardo E6 engine. One of the fuels investigated in the study was a methyl ester derived from algae [21-23]. During the initial testing phase, various factors including engine speed, compression ratio and injection timing were considered, while the engine torque ranged from 0.5 to 15 Nm. In the second trial, the injection timings were varied within a range of 20° to 45° BTDC. The study findings suggested that adjustments to the injection timing and load might be necessary due to the distinct properties of different biofuels [24-29].

## Materials and Method

### Materials

In this investigation Spirulina biodiesel and additive borax

decahydrate was purchased from the local market. Spirulina biodiesel was heated for 30 min to remove moisture content from this biodiesel. Many researchers suggested that biodiesel should be preheated for some before its use because biodiesel fuels have some moisture content when stored for a long time after its production. Characterization data of biodiesel metallic nanoparticles reveal crucial information about their physical and chemical properties, enabling a deeper understanding of their potential applications in the fields of renewable energy and environmental sustainability. These data typically encompass metallic nanoparticle size distribution, surface morphology, composition, stability, and surface charge, all of which play pivotal roles in determining their performance as catalysts, carriers for drug delivery, or additives for enhancing fuel combustion efficiency. Accurate characterization allows researchers and engineers to tailor biodiesel metallic nanoparticles for specific tasks, optimizing their functionality and harnessing their full potential to address pressing global challenges related to energy and pollution.

In the realm of biofuel production, comprehensive characterization studies of metallic nanoparticles are imperative to ensure their effective utilization and safety. These studies encompass a multifaceted approach, including rigorous analysis of particle size, shape, composition, surface properties, and stability. Furthermore, in-depth investigations into metallic nanoparticle interactions with biofuel components and potential biological or environmental impacts are essential. By providing a robust body of characterization data, researchers can confirm the suitability of metallic nanoparticles for enhancing biofuel production processes, while simultaneously addressing concerns related to their potential ecological and biological implications, fostering a more sustainable and responsible biofuel industry.

The metallic nanoparticles under investigation are synthesized via a chemical reduction method. In this process, chloroauric acid ($HAuCl_4$) was used as the precursor, and sodium citrate served as the reducing agent and stabilizer. The synthesis was carried out in a controlled environment with the solution maintained at a temperature of 80 °C under constant stirring. This method yielded well-dispersed metallic nanoparticles with an average size of approximately 20 nm, as confirmed by scanning electron microscopy (SEM) analysis. These metallic nanoparticles hold promise for various applications in nanotechnology and materials science due to their controlled synthesis conditions and unique properties.

## Characterization of borax decahydrate

Borax decahydrate ($Na_2B_4O_7.10H_2O$) underwent characterization, revealing its attributes as a white crystalline substance with moderate solubility in cold water, high solubility in hot water, and limited solubility in ethanol [30-33]. It displayed a melting point initiation at approximately 50 °C (122 °F) and complete decomposition around 75 °C (167 °F), leading to the formation of anhydrous borax ($Na_2B_4O_7$) at elevated temperatures. Its density measured approximately 1.73 g/cm$^3$, and it exhibited a monoclinic crystal structure. The purity grade of the borax decahydrate conformed to the specifications required for our research. The figure 1 shows SEM images of borax decahydrate taken from the reference [22]. The SEM images observed the presence of clustered formations alongside layered crystalline structures. This occurrence can be attributed to the high concentration of boron structures found in borax. Additionally, the SEM images revealed that the borax used during sample preparation was in a microscale form.

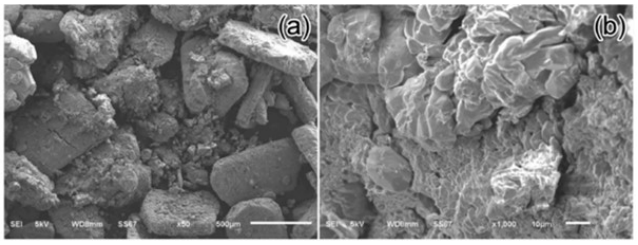


**Figure 1:** Reproductions of borax decahydrate powder captured using SEM **(a)** at a 50-fold magnification and **(b)** at a 1000-fold magnification [22].

## Sample preparation

All sample preparations are shown in figure 2 and figure 3. Spirulina biodiesel is initially added with diesel at a 10% ratio (90% diesel + 10% Spirulina biodiesel), which is nominated as SB10. Prepare the sample of this blend of Spirulina biodiesel with diesel and add borax decahydrate in different ratios like 1 g, 3 g, 5 g, and 7 g in four compositions to find out its possibilities as an alternative fuel for diesel engine. Five samples are prepared first SB10 (90% diesel + 10% Spirulina biodiesel), secondly SB10B1 (90% diesel + 10% Spirulina biodiesel + 1 g borax decahydrate), third SB10B3 (90% diesel + 10% Spirulina biodiesel + 3 g borax decahydrate), fourth SB10B5 (90% diesel + 10% Spirulina biodiesel + 5 g borax decahydrate), and fifth sample SB10B7 (90% diesel + 10% Spirulina biodiesel + 7 g borax decahydrate). The picture of different samples is shown in the figure 3.

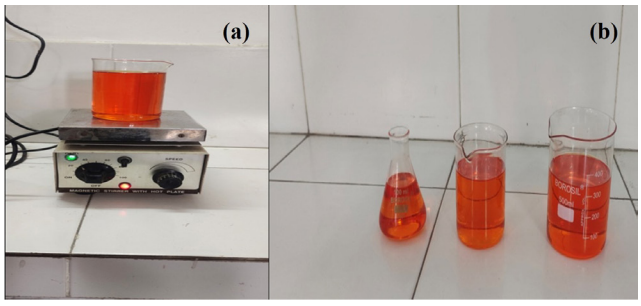


**Figure 2: (a)** Moisture removal and **(b)** Final biodiesel sample.




**Figure 3:** Different samples of Spirulina biodiesel, diesel, and borax decahydrate.

## Experimental setup

In this investigation, the performance and emissions characteristics of samples of Spirulina biodiesel SB10 with different compositions of borax decahydrate on a 1-cylinder DI diesel engine and results were compared with diesel fuel. It also investigated the ideal composition of borax decahydrate by mixing Spirulina biodiesel and diesel to evaluate the impact on performance and emissions metrices and to check for any specific emissions issues when using biodiesel fuel with mixing metallic nanoparticles in a CI engine (Figure 4 and figure 5). The following steps of experimental work have been planned out for this practical work: (a) Prepare the sample of the blend of Spirulina biodiesel with diesel and add borax decahydrate in different ratios like 1 g, 3 g, 5 g, and 7 g in four compositions. (b) To determine performance and emission characteristics for various test fuels under different load situations, such as brake power, BSFC, Air-fuel ratio, CO, $CO_2$, $NO_x$ (Nitrogen oxides) and HC emissions. (c) Analyze experimental data from CI engines running on samples of Spirulina biodiesel with diesel and add borax decahydrate in different ratios and compare the engine's performance characteristics and emissions.

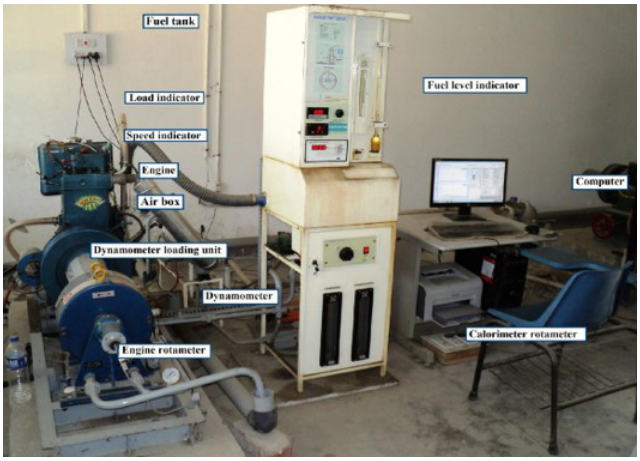


**Figure 4:** Diesel engine setup.

## Emission and performance measurement

### Exhaust five gas analyzer

Five gas emission analyzers can detect all emissions, including CO, $CO_2$, $NO_x$, HC, and unused oxygen. The cable in question is connected from one end to the inlet of the analyzer and from the other end to the exhaust gas outlet. In order for the analyzer to function correctly, it must be constantly charged. The measurement technique is based on the "non-dispersive infrared absorption" theory of light absorption in the infrared domain. The light source's broadband infrared radiation travels through a gas-filled chamber typically filled with methane or $Co_2$. This gas absorbs light of a specific wavelength, and its amount corresponds to the gas's concentration. Before it is detected using a pyroelectric detector, all other wavelengths are eliminated by a narrow bandwidth optical filter at the end of the chamber. At the diesel engine experimental setup's fixed engine speed (1500 rpm), the experiments were run under five distinct loading situations (zero load, 25% to 100% loads).

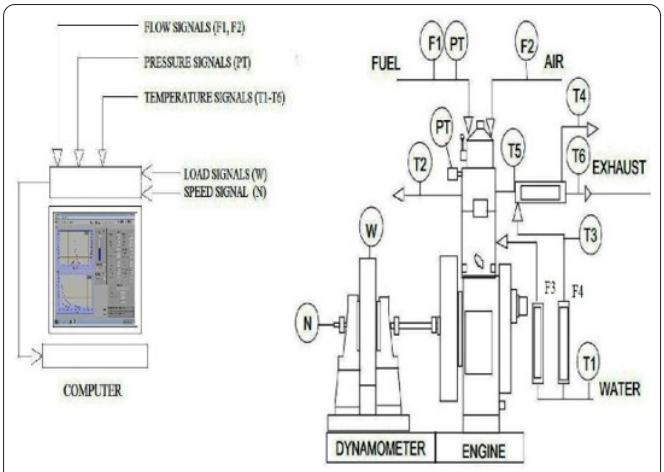


**Figure 5:** Line diagram of engine test rig.

# Results and Discussion

The experimental data obtained from the study are presented and subsequent parts in-depth investigate these results. The study's primary goal was to calculate the performance and emission metrices of CI engines using blended Spirulina biodiesel and borax decahydrate as metallic nanoparticles (Table 1), and the findings were compared to baseline information on neat diesel (Table 2). Table 3 presents different sensors location.

## Performance characteristics

### Brake thermal efficiency

The changes in BTE and different loading conditions for all fuel samples are expressed in (Figure 6). The BTE at 0%

**Table 1:** Different properties of the mixture of different compositions of borax decahydrate, Spirulina biodiesel, and diesel.

| Properties | Diesel | SB10 | SB10B1 | SB10B3 | SB10B5 | SB10B7 |
|---|---|---|---|---|---|---|
| Kinematic viscosity (cst) at 30 °C | 2.71 | 2.95 | 3.23 | 3.48 | 4.1 | 4.6 |
| Density (g/cc) | 0.829 | 0.836 | 0.841 | 0.848 | 0.852 | 0.878 |
| Cloud point (°C) | 5 | 5 | 6 | 6.4 | 6.6 | 7 |
| Pour point (°C) | 3 | 4.1 | 4.7 | 5 | 5.6 | 6 |
| Flash point (°C) | 52 | 58 | 60 | 66 | 73 | 85 |
| Fire point (°C) | 63 | 69 | 74 | 74 | 85 | 92 |
| Calorific value (MJ/kg) | 44 | 41.578 | 41.271 | 40.963 | 40.659 | 39.25 |

for diesel, SB10, SB10B1, SB10B3, SB10B5, and SB10B7 was 0.205%, 0.975%, 1.76%, 1.81%, 1.82%, and 1.47% respectively. At no load, SB10B3 gives maximum efficiency compared to other fuels. At 25% load, SB10B3 blends to give a maximum efficiency of 20.82%. It is because SB10B3 has 5 to 7% more oxygen and produces less CO and $CO_2$ than other fuels, so it helps to improve the combustion chamber of the engine and advance fuel injection timing. At half loading condition, diesel and SB10B7 have approximately equal BTE, and SB10B3 have a maximum efficiency of 29.83% as compared to other fuels, but at 75% load, diesel has 1.2% higher efficiency than SB10B7 because diesel has higher calorific value as compared to SB10B7. At full load diesel, SB10, SB10B1, SB10B3, SB10B5, and SB10B7 have 34.64%, 35.76%, 35.83%, 36.06%, 35.53%, and 34.62% BTE accordingly. The higher BTE might be because of better combustion due to the presence of additive materials and additional lubricity of blends i.e., SB10B1 and SB10B3 give better efficiency than other fuel samples. When comparing the various blends, it can be concluded that SB10B3 exhibits the highest BTE. This superior performance can be attributed to its improved combustion characteristics compared to other blends.

**Table 2:** Technical specifications of diesel engine.

| | |
|---|---|
| Make | Kirloskar |
| Model No | TV1 |
| No of cylinders | 1 |
| Engine capacity (cc) | 661 |
| Bore and stroke length | 87.5 mm, 110 mm |
| Orifice diameter | 20 mm |
| Engine power | 5.2 kW@1500 rpm |
| Fuel injection angle | 23° bTDC |
| Exhaust valve open/Close position | 35.5° bBDC/4.5° aTDC |
| Inlet valve open position | 4.5° bTDC/35.5° aBDC |
| Drum brake diameter | 185 mm |
| Eddy current dynamometer | Model AG10 |

**Table 3:** Different sensors location.

| | |
|---|---|
| T1 | Water inlet temperature of engine |
| F1 | Consumption of fuel |
| T2 | Water outlet temperature of engine |
| F2 | Consumption of fuel |
| T3 | Water inlet temperature of calorimeter |
| F3 | Engine water flow |
| T4 | Water outlet temperature of calorimeter |
| F4 | Calorimeter water flow |
| T5 | EGT before calorimeter |
| T6 | EGT after calorimeter |
| N | Speed sensor |
| W | Load sensor |
| PT | Cylinder pressure and injection pressure sensor |

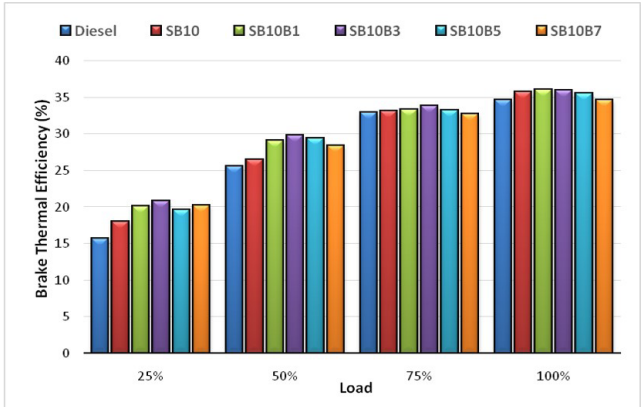


**Figure 6:** BTE vs load.

## Brake specific fuel combustion

The BSFC is shown in figure 7 for various loads and fuels. Engines' brake power output and the fuel mass flow rate are used to estimate the BSFC. Diesel has a greater BSFC than other fuels at a load of 25%, whereas SB10B7 has a higher BSFC with a load of 75%. Diesel and biodiesel have the same BSFC when both are fully loaded. The decrease in fuel's calorific value is due to the higher biodiesel compositions in the blends.

## Air-fuel ratio

Figure 8 illustrates the fluctuation in air-fuel ratio for various loads and fuels. Compared to other blends, diesel has a lower air-fuel ratio at 0%, 25%, and 50% load conditions. Due to the lower calorific value of the blends caused by the increased amount of biodiesel, SB10B7 exhibits a higher air-fuel ratio of 25%.

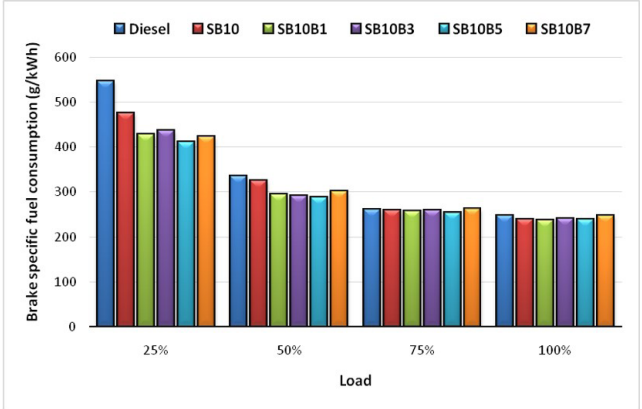


**Figure 7:** BSFC vs load.

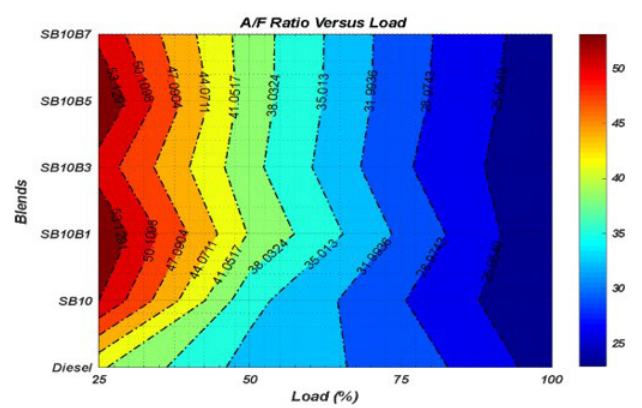


**Figure 8:** Air-fuel ratio vs load.

## Emission performance

### Carbon monoxide

Figure 9 illustrates the fluctuation in CO for various loads and fuels. The data indicate that diesel emits significantly more CO than other blends at no load. CO emission is seen to decrease as load increases. However, due to superior combustion for all biodiesel blends, diesel emits a more significant percentage of CO than other blends under all load conditions. Because SB10B3 has 7% to 8% more oxygen than other blends, it produces the least CO of all the fuels.

### Carbon dioxide emission

Figure 10 illustrates the change in $CO_2$ for various loads and fuels. Diesel and SB10B7 emit more $CO_2$ than other fuels when there is no load. It has been noted that the percentage of $CO_2$ rises with increasing load conditions; this is because the bulk of fuel also rises with increasing load. When the load is 50% and 100%, SB10B3 emits the least $CO_2$. Because the air-fuel mixture produces more $CO_2$ when running faster, this is because of this.

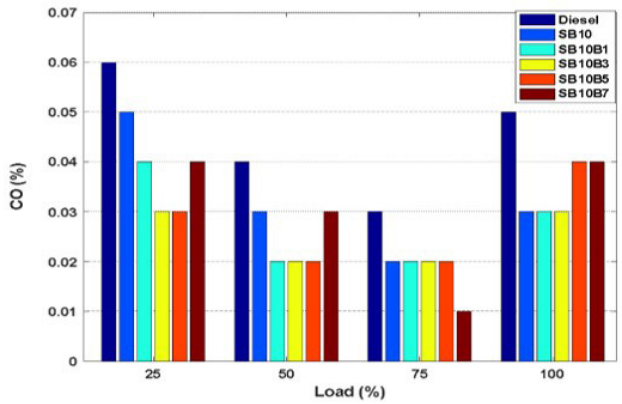


**Figure 9:** Carbon monoxide vs load.

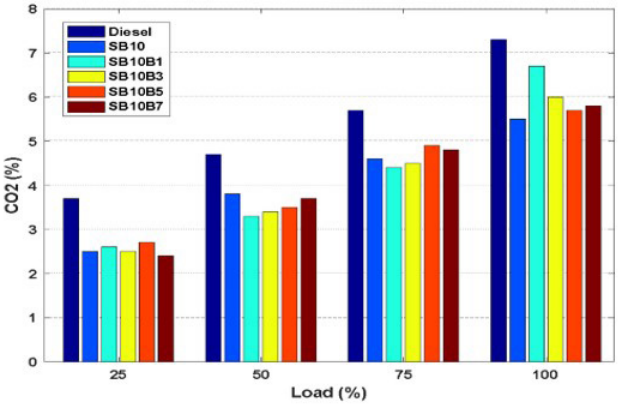


**Figure 10:** Carbon dioxide vs load.

### Hydrocarbon emission

Figure 11 depicts the variation in HC for various loads and fuels. Diesel engines SB10, SB10B1, SB10B3, SB10B5, and SB10B7 emit 41, 38, 39, 40, 38, and 35 ppm HCs at zero load. Due to better fuel combustion than other engines, SB10B7 produces less HC at 0% and 25% load conditions. Due to the fact that the components of blended fuel often have larger molecular weights than those found in diesel fuel and, as a result, have higher boiling and condensing temperatures, it has been shown that biodiesel blends up to 75% loading condition produce fewer HCs. Biodiesel blends create higher HC than diesel under full load conditions because more fuel is injected due to a richer mixture form and incomplete combustion occurs.

### Nitrogen oxides emission

Figure 12 illustrates the fluctuation in $NO_x$ for various loads and fuels. When the load is 0%, SB10B7 produces more $NO_x$ than other engines. Because the mass of blended fuel increases with an increase in biodiesel concentration, greater temperatures are produced during fuel combustion. The higher air-fuel ratio in SB10B7, resulting from the lower calorific value and increased biodiesel content, leads to an increase in $NO_x$ emissions. Consequently, SB10B7 exhibits higher $NO_x$ emissions across all load conditions.

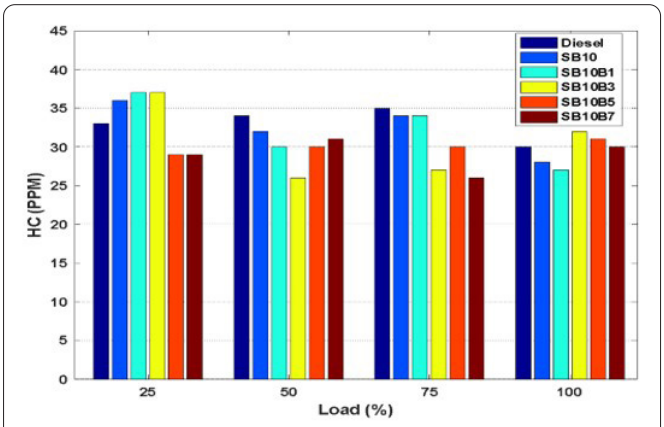


**Figure 11:** Unburned hydrocarbon vs load.

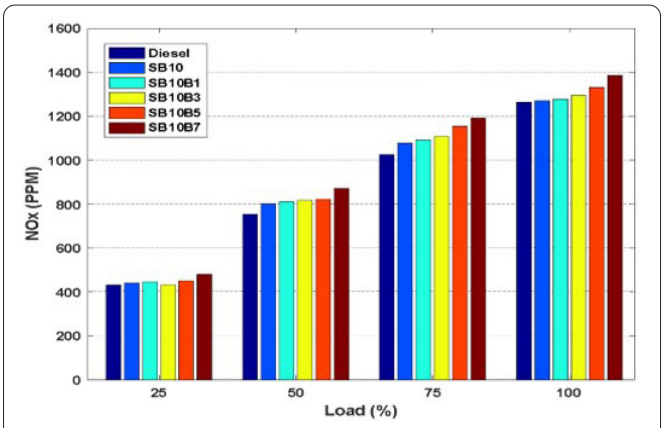


**Figure 12:** $NO_x$ vs load.

## Conclusion

Compared to diesel, SB10B3 recorded a better BTE. The cause of it is proper combustion and early fuel injection. Based on its BTE, SB10B3 can be regarded as the best blend out of all the combinations. When under full load, the SB10B3 brakes have a thermal efficiency of 36%. SB10B7 demonstrates higher BSFC compared to diesel fuel across all loading conditions.

At the same time, SB10B3 recorded less BSFC than diesel, which indicates that SB10B3 was the best blend based on fuel consumption. For all load conditions, SB10B3 showed a lower air-to-fuel ratio than diesel. Metallic nanoparticle-added samples have less CO and $CO_2$ than diesel fuel at all loading conditions because they have 8% to 9% more oxygen contents than diesel. Due to this, better combustion takes place. SB10B3 produces less CO among all the fuel blends. It was found that because more fuel is injected at full load, a richer mixture forms, and incomplete combustion occurs. SB10B7 has a more significant amount of unburned HC than diesel does at full load. However, SB10B3 produces 5% less unburned HC than diesel under all loading conditions. When biodiesel concentration is increased, more $NO_x$ is released into the atmosphere due to the increased mass of blended fuel, which raises the temperature at which fuel is burned. SB10B7 causes an up to 25% increase in $NO_x$ emissions under all load conditions.

## Acknowledgements

None.

## Conflict of Interest

None.

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