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## Research Article

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# Performance and Emission Analyses of a Diesel Engine Fueled with Mango Seed

## Biodiesel-Butanol Blend Enhanced with Titanium Dioxide Nanoparticles

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### Abstract

This study investigates the influence of nano-additive titanium dioxide (TiO<sub>2</sub>) in mango seed biodiesel (MSB), butanol (B) and diesel ternary fuel blends on performance and emission characteristics of diesel engine. TiO<sub>2</sub> nano-additive is mixed in different proportions with ternary blends through ultra-sonication to prepare test samples. Some key findings were highlighted: (i) Brake specific fuel consumption (BSFC) was increased by 21.66%, 17.56%, 13.88%, 11.88% and 6.58% for MSB20B5, MSB20B5TiO<sub>2</sub>25ppm, MSB20B5TiO<sub>2</sub>50ppm, MSB20B5TiO<sub>2</sub>75ppm and MSB20B5TiO<sub>2</sub>100ppm blends, respectively compared to conventional diesel. (ii) Brake thermal efficiency (BTE) of MSB20B5TiO<sub>2</sub>100ppm exhibited 1.58% lower than conventional diesel followed by MSB20B5TiO<sub>2</sub>75ppm, MSB20B5TiO<sub>2</sub>50ppm, MSB20B5TiO<sub>2</sub> 25 ppm and MSB20B5, respectively. (iii) NO<sub>x</sub> emission of MSB20B5, MSB20B5TiO<sub>2</sub> 25 ppm, MSB20B5TiO<sub>2</sub>50ppm, MSB20B5TiO<sub>2</sub>5ppm and MSB20B5TiO<sub>2</sub>100ppm exhibited 9.55%, 17.97%, 28.65%, 34.83% and 51.68% higher than conventional diesel; (iv) HC emissions was reduced by 8.69%, 13.93%, 19.39%, 24.84% and 20.09% for MSB20B5, MSB20B5TiO<sub>2</sub>25ppm, MSB20B5TiO<sub>2</sub>50ppm, MSB20B5TiO<sub>2</sub>75ppm and MSB20B5TiO<sub>2</sub>100ppm, respectively compared to conventional diesel.

**Keywords:** Biofuel; Titanium dioxide nanoparticle; Nano additive; Mango seed biodiesel; Diesel engine

## Nomenclature

| Abbreviation    | Description                                | Abbreviation                   | Description                                                 |
|-----------------|--------------------------------------------|--------------------------------|-------------------------------------------------------------|
| ASTM            | American society for testing and materials | ppm                            | Part per million                                            |
| B               | Butanol                                    | HC                             | Hydrocarbon                                                 |
| BSFC            | Brake specific fuel consumption            | NOx                            | Nitrogen oxides                                             |
| BTDC            | Before top dead centre                     | MSB                            | Mango seed biodiesel                                        |
| BTE             | Brake thermal efficiency                   | MSB20B5                        | Diesel 75%, MSB 20%, butanol 5%                             |
| CO              | Carbon monoxide                            | MSB20B5TiO <sub>2</sub> 25ppm  | 75% Diesel, 20% MSB, 5% butanol and titanium dioxide 25ppm  |
| CO <sub>2</sub> | Carbon dioxide                             | MSB20B5TiO <sub>2</sub> 50ppm  | 75% Diesel, 20% MSB, 5% butanol and titanium dioxide 50ppm  |
| EGT             | Exhaust gas temperature                    | MSB20B5TiO <sub>2</sub> 75ppm  | 75% Diesel, 20% MSB, 5% butanol and titanium dioxide 75ppm  |
| FFA             | Free fatty acid                            | MSB20B5TiO <sub>2</sub> 100ppm | 75% Diesel, 20% MSB, 5% butanol and titanium dioxide 100ppm |

## 1. Introduction

Transportation, industrialization, power production, agriculture and globalization have enhanced fossil demands world-widely. As fossils availability is limited in nature and depleting very fast, hence, biofuel production can be emerging research requirement as an alternate. Biofuel from different waste biomass can be favorable choice for customers and lead global fuel market due to their sustainable, renewable and environment friendly nature [1]. As of now, biofuel production is rapidly increasing as a substitute for petroleum diesel around the world owing to its numerous economic and environmental advantages [2]. Hence, it is bound to improve the performance and reduce the emission parameters to minimize global issues like global warming, ozone depletion and acid rain. In the past decade, biofuel was produced from different feedstocks to mitigate the issues of rapid depletion of conventional fuels, save environment and sustainable development [3,4]. Biodiesel offers a green alternative as it is renewable, non-explosive, non-flammable, non-toxic, and breaks down in the soil without adverse environmental effects. Thus, it is cleaner and contributes to lower emission levels than conventional diesel [5,6]. Despite its benefits, biodiesel use is limited by low energy content and elevated density, BSFC, viscosity, and NO<sub>x</sub> emissions. Biodiesel limitations can be mitigated by additives like oxygenates, cetane boosters, metals, lubricants, antioxidants, and cold flow agents; alcohol helps improve flow by lowering viscosity [7]. Butanol, having a higher cetane number, is considered a superior biofuel alternative to methanol and ethanol. The favorable properties of butanol such as less corrosiveness, higher cetane number, and better blending stability with conventional diesel make it a viable alcohol-based biofuel [8,9]. Butanol, with better diesel fuel compatibility, higher energy content, and lower water solubility than other alcohols, is selected for this study. The integration of biodiesel reduces thermal efficiency, power, and engine torque, but raises peak cylinder pressure and specific fuel consumption. CO, PM, and HC emissions decline, with a slight increase in NO<sub>x</sub> and NO levels [10]. The inclusion of butanol in the fuel blend enhances biodiesel's cold flow characteristics. However, it is observed that butanol increases BSFC, HC emissions, and peak combustion parameters but reduces CO, exhaust temperature, NO<sub>x</sub>, thermal efficiency, and smoke emissions [11,12]. Lower energy content in biodiesel and butanol limits performance, but fuel additives such as oxygenates, metals, cetane improvers, and antioxidants enhance overall quality. Metal additives decrease pour point and viscosity, increasing flash

point. Oxygenates improve combustion through oxygen enrichment and modify density, energy values and viscosity. Antioxidants raise cetane number and oxidative stability but lower calorific value [13,14]. Although nano-particles may cause injector blockage due to surface-induced clumping, their high energy density contributes to superior combustion behavior and ignition acceleration [15]. Nano-particles, with their surface area and high reactivity, lead to faster oxidation of fuel blends, which raises boosts energy density and combustion enthalpy. The high reactivity and atomization of nano-fluid fuels shorten ignition delay, accelerate combustion initiation, and increase heat release rate and in-cylinder [16]. Fangsuwannarak and Triratanasirichai [17] evaluated engine performance using diesel, B5+palm biodiesel, TiO<sub>2</sub>-diesel, and B5+palm biodiesel with TiO<sub>2</sub>. They observed that TiO<sub>2</sub>-blended fuels (1700–3000 rpm) increased power by 1.36% and 7.78%, and torque by 1.53% and 1.01% over B5 and diesel, respectively, while TiO<sub>2</sub>-diesel exhibited reduction in BSFC by 13.22% and lowering CO<sub>2</sub>, CO, and NO<sub>x</sub> emissions. Karthikeyan and Prathima [18] tested B20 microalgae biodiesel with TiO<sub>2</sub> and SiO<sub>2</sub> nanoparticles in a naturally aspirated DI engine, observing improved calorific value relative to diesel. Due to their high surface area, nano-additives enhance air–fuel interaction, reducing SFC and improving combustion and brake thermal efficiency. Also, TiO<sub>2</sub>–SiO<sub>2</sub> blends emit less HC and CO but more CO<sub>2</sub> and NO<sub>x</sub> than diesel. Silva et al. [19] explored the inclusion of TiO<sub>2</sub> nanoparticles which affect engine performance and emissions, noting that their addition increased diesel’s calorific value by 0.59%. At full load, there was a 0.9% increase in BTE, a 21.28% decrease in BSFC, and reductions of 18.36% in HC and 25% in CO emissions, with a 32% rise in NO<sub>x</sub> emissions. Sungur et al. [20] observed that TiO<sub>2</sub>-diesel blends reduce exhaust gas temperature and CO, improve thermal efficiency, with negligible impact on NO<sub>x</sub> emissions. Khan et al. [21] reported that the addition of graphene oxide and n-butanol to nigella sativa biodiesel enhanced BTE and lowered emissions through better oxygenation. Graphene oxide levels were adjusted from 30 to 120 ppm, maintaining a constant 25% biodiesel and 10% n-butanol blend. BTE improved by 18.37% when 90 ppm graphene oxide and 10% n-butanol were added to a 25% biodiesel blend. At every GO NP concentration, n-butanol improved air–fuel interaction and combustion, resulting in reduced BSFC. Higher NO<sub>x</sub> was observed at 90 ppm GO NPs with n-butanol, whereas 120 ppm GO led to reduced emissions. Emission levels of CO, smoke, and HC dropped with 90 ppm GO NPs and 10% n-butanol in the 25% biodiesel blend. Maniganda et

al. [22] found that  $\text{TiO}_2$ ,  $\text{CeO}_2$ , CNT, CuO,  $\text{Al}_2\text{O}_3$ , and hydrogen altered combustion and emissions in dual-fuel engines, with  $\text{TiO}_2$  cutting CO most significantly and CNT reducing  $\text{NO}_x$  and HC by 33% and 90%. Sajin et al. [23] studied the effect of ZnO nanoparticles (20 and 40 ppm) with neat mango seed biodiesel (MSB) on performance and emissions of CI engine and revealed that M100ZnO40ppm reduced  $\text{NO}_x$ , HC, CO and smoke emissions by 4.2%, 2.89%, 3.69% and 3.58% respectively compared to neat MSB.

Literature on diesel engine behavior suggests that the use of non-edible seed oil-based biodiesel blends holds potential to replace mineral diesel and reduce future fuel dependency. India is a largest producer of mango which was 25 MT in 2024. Mango seed oil is a non-edible oil, so its use does not compete with food resources. Approximately 20% of the mango is used for food production, while 35–60% of it forms waste components, primarily the seed and shell. In the current work, mango seeds were used to extract biodiesel fuel. Bio-butanol is a promising biofuel due to its superior energy density compared to methanol and ethanol, low corrosiveness, and limited tendency to absorb water. Bio-butanol, produced mainly from the fermentation of cellulose glucose, and starch stands out for its lower environmental impact, food security. Mango seed biodiesel exhibits lower energy content and higher viscosity, which are viewed as its primary downsides. In order to mitigate this issue, the study used bio-butanol, which is cleaner, has a lower cetane number, and offers enhanced combustion. While numerous studies have investigated ternary fuels [xiii-xviii], very limited studies examined the effects of blending them with 25 ppm, 50 ppm, 75 ppm, and 100 ppm of metal-doped titanium nano additives. As a result, the novelty of this study is focused on analyzing ternary fuels (Diesel 75% +biodiesel 20% + butanol 5%) along with varying doses of metal-doped titanium nano additives in a single-cylinder diesel engine setup. The physico-chemical properties—density, kinematic viscosity, calorific value, and flash/fire point—of the blends were evaluated in accordance with ASTM standards. Further, performance parameters (BTE, BSFC, and EGT) and emission parameters (CO, HC,  $\text{NO}_x$ , and  $\text{CO}_2$ ) of diesel and its blends were evaluated on a 4-stroke, single-cylinder, water-cooled diesel engine under varying loads without any modifications to its design. Lastly, the present results are compared with earlier novel studies.

## **2. Materials and methods**

## **2.1. Production of biodiesel from mango oil**

The first important step in producing biodiesel is to measure the oil's free fatty acid (FFA) content accurately, if this value exceeds 2 wt%, esterification must be performed to prevent soap formation before transesterification begins. The mango oil used to generate biodiesel was gathered from the Madan Mohan Malaviya University of Technology, Gorakhpur, U.P, India through Soxhlet apparatus. Two critical steps have been successfully completed in the production process: firstly, esterification followed by transesterification, catalyzed by an alkaline agent. Previous studies [24,25] have also examined the generation of biodiesel at elevated FFA content with same processes.

### **2.1.1 Acid-catalyzed esterification**

Here, the process consists of reacting alcohol with glyceride (mango oil), where alcohol is the reactant and p-toluenesulfonic acid (PTSA) acts as the catalyst to minimize excess FFA. The oil, once filtered, is dehydrated to speed up and enhance the reaction. The oil is first heated to 120 °C, held at that temperature for 40–50 minutes, and then brought down to a temperature of 60 °C. The procedure serves to accelerate operations and remove moisture from the filtered oil. Then, a mixture of catalyst and methanol are incorporated into the oil. To ensure thorough mixing, a magnetic stirrer spinning at nearly 500 rpm was used for about 2.30 hours. The mixture was prepared with a catalyst concentration of 0.5% (w/w) and an oil-to-alcohol ratio of 1:6. The post-reaction product contains esterified oil along with leftover methanol, impurities and catalyst. The solution was allowed to rest in a decanting funnel for close to 6 hours, which enabled the separation of its components. The oil, still containing extra water and alcohol, was heated in a rotary evaporator under vacuum at 100 °C for one hour. The esterified oil exhibited an FFA content of 1.846%, which matched the theoretical range and permitted continuation of the transesterification process. This permitted the continuation of the transesterification process.

### **2.1.2 Base-catalyzed esterification**

The process concluded with a alkali-catalyzed transesterification reaction to form biodiesel, which was relatively simple because the free fatty acid content had already been reduced with methanol. A combination of oil from various esterification processes, (1% w/w) KOH pellets, (20% w/w) methanol and waste cooking

oil to catalyst ratio (6M:1) was blended to form the mixture.

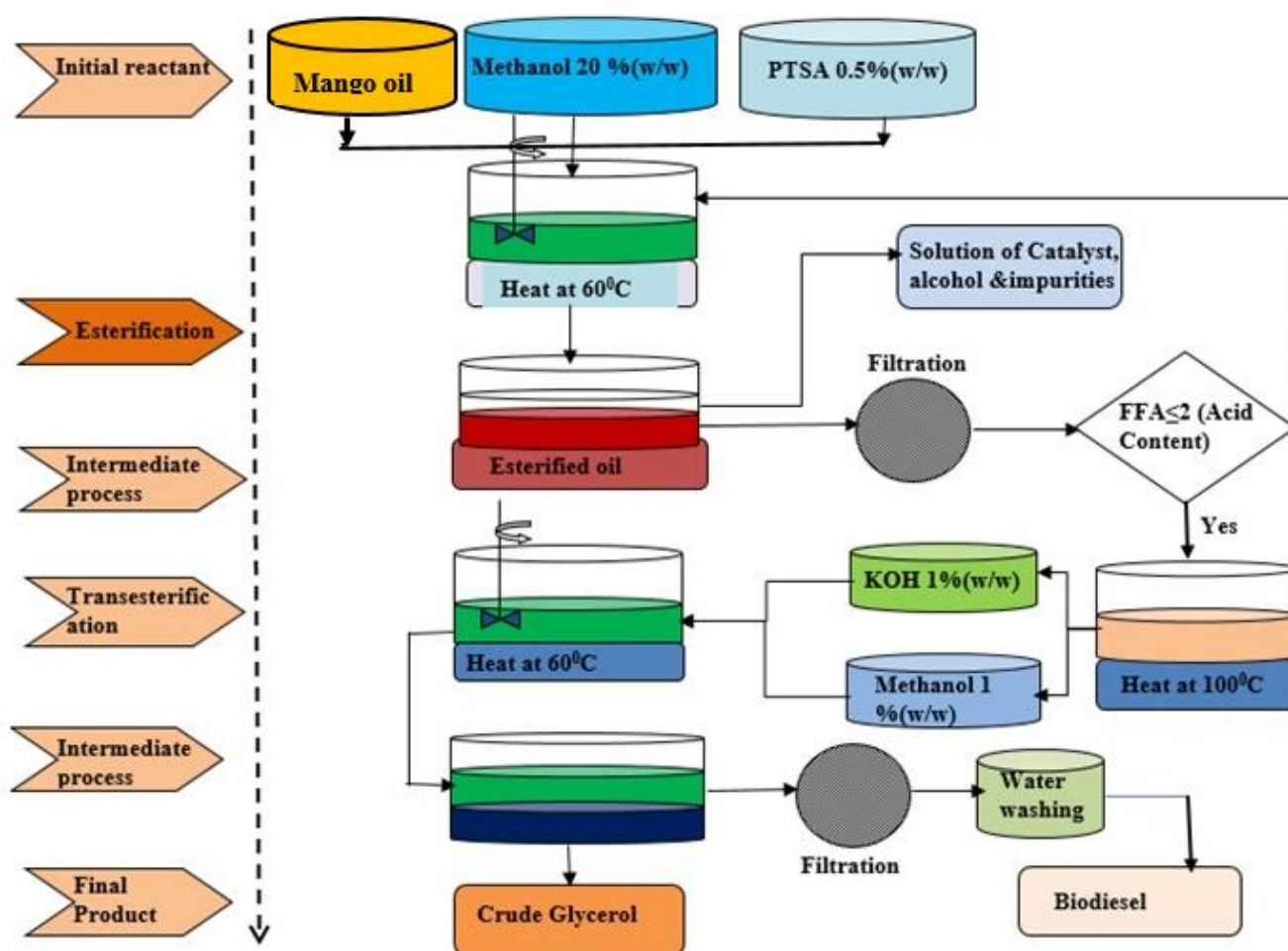


**Fig. 1.** Flow diagram of production of biodiesel.

After being cooled to 60 °C and stirred for two hours at 1200 rpm, the mixture was placed in a funnel and left undisturbed for 12 hours. At the end of the process, both biodiesel and unrefined glycerol were produced. The crude glycerol, being denser, accumulated on the surface and was extracted using filtration and biodiesel was obtained by purifying the esters with hot water after the completion of base-catalyzed transesterification as displayed in **Fig. 1**. In addition, the methyl ester of mango oil underwent testing of its physico-chemical properties following ASTM guidelines, as detailed in Table 1.

### 2.1.3 Preparation of test blends

Titanium dioxide nanoparticles are more effective due to their high oxygen content and surface energy to react with other molecules which improves the fuel properties and combustion process. The conventional

diesel purchased from Indian Oil Corporation Limited (local oil station), Gorakhpur. Other chemicals and  $\text{TiO}_2$  nanoparticles purchased from Indian Scientific Corporation, Lucknow, India.  $\text{TiO}_2$  nanoparticles (25ppm, 50ppm, 75ppm and 100ppm) are dispersed in fixed diesel-biodiesel-butanol as MSB20B5 (75% diesel - 20% biodiesel - 5% butanol) ternary blend through magnetic stirring followed by ultrasonication to ensure the fuel homogeneity, spray, stability and flow characteristics. These blends are individually ultrasonicated for 30 min at 60 °C with a frequency of 50 Hz and power 120 W before use in diesel engine. Four test fuel samples are prepared and named as MSB20B5 $\text{TiO}_2$ 25ppm (75% diesel+20% biodiesel+5% butanol+ $\text{TiO}_2$ 25ppm), MSB20B5 $\text{TiO}_2$ 50ppm (75% diesel+20% biodiesel+5% butanol+ $\text{TiO}_2$ 50ppm), MSB20B5 $\text{TiO}_2$ 75ppm (75% diesel+20% biodiesel+5% butanol+ $\text{TiO}_2$ 75ppm) and MSB20B5 $\text{TiO}_2$ 100ppm (75% diesel+20% biodiesel+5% butanol+ $\text{TiO}_2$ 100ppm) respectively. **Fig. 2** and **Fig. 3** show the experimental setup for blending of  $\text{TiO}_2$  nanoparticles and prepared test fuel samples respectively. The important properties of fuel samples are evaluated as per ASTM standards and presented in Table 1.

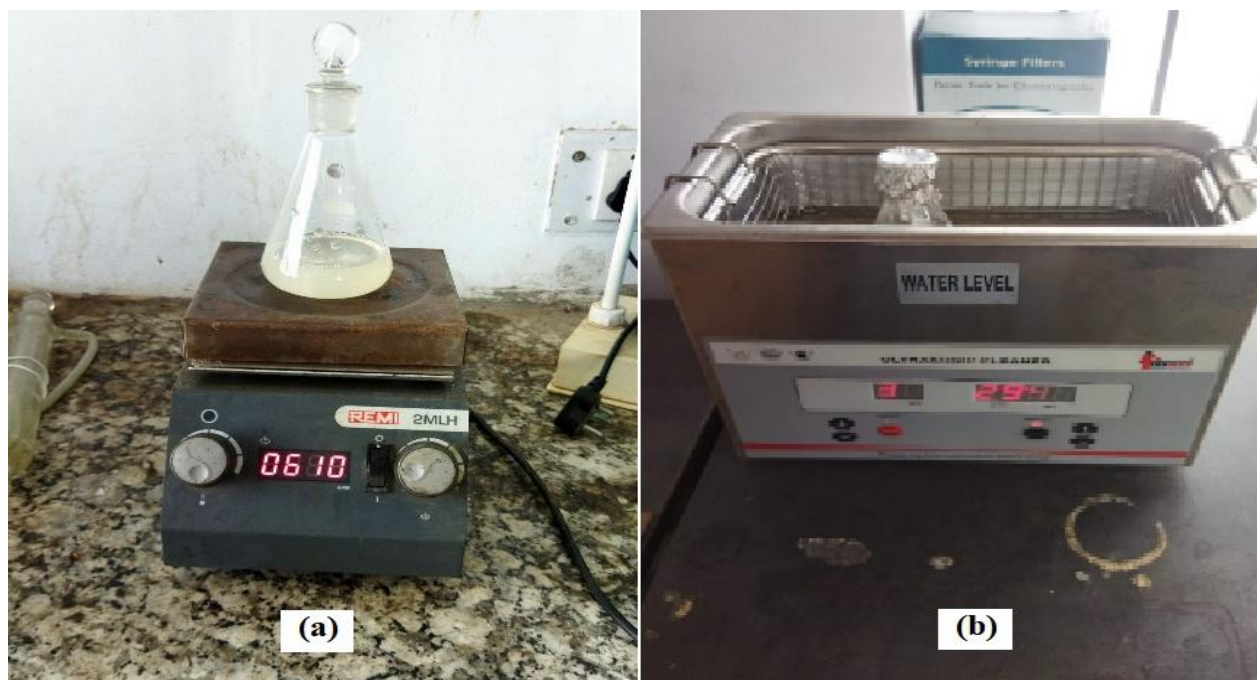


**Fig. 2** Blending of  $\text{TiO}_2$  nanoparticles (a) Magnetic stirring (b) Ultrasonication



**Fig. 3** Prepared test fuel samples.

**Table 1.** Important properties of prepared test samples.

| Properties/<br>Fuel                            | Diesel | MSB20B5 | MSB20B5+<br>TiO <sub>2</sub> 25 ppm | MSB20B5<br>+TiO <sub>2</sub> 50<br>ppm | MSB20B5<br>+TiO <sub>2</sub> 75<br>ppm | MSB20B5<br>+TiO <sub>2</sub> 100<br>ppm | ASTM<br>Standard |
|------------------------------------------------|--------|---------|-------------------------------------|----------------------------------------|----------------------------------------|-----------------------------------------|------------------|
| Density<br>(kg/m <sup>3</sup> )                | 830    | 838     | 837                                 | 836                                    | 834                                    | 833                                     | D-1298           |
| Flash point<br>(°C)                            | 61     | 75      | 73                                  | 71                                     | 69                                     | 68                                      | D-93             |
| Fire point<br>(°C)                             | 65     | 83      | 78                                  | 76                                     | 75                                     | 73                                      | D-93             |
| Kinematic<br>viscosity<br>(mm <sup>2</sup> /s) | 2.76   | 2.95    | 2.93                                | 2.91                                   | 2.89                                   | 2.87                                    | D-445            |
| Heating<br>value<br>(MJ/kg)                    | 42.97  | 42.11   | 42.21                               | 42.25                                  | 42.31                                  | 42.38                                   | D-240            |

### 3. Experimental setup

The engine setup, outlined in Table 2, incorporates a 4-stroke, single-cylinder, water-cooled, DI diesel engine with natural aspiration and a computer-controlled variable port injection pressure system. The engine configuration and setup are detailed in **Fig. 4** and **Fig. 5**. To measure the crank angle, a crankshaft with an attached crank angle encoder is used, and cylinder pressure is monitored by a piezoelectric pressure transducer mounted on the chamber head. Oil levels were checked during every hydrogen induction inspection in the engine, with ongoing monitoring of coolant temperature to safeguard against overheating. To prevent both sediment deposits and undesirable chemical reactions in the fuel line, a separate gas tank and fuel line are employed. By using a pressure regulator, the hydrogen pressure outside the tank was decreased by 5 bar, and manual control over the hydrogen supply enabled adjustments for different fractions or a total shutoff during unanticipated situations. The flow rate of hydrogen was adjusted by a regulating check valve, and alterations in the volumetric flow rate were measured using a thermal mass flow meter. Hydrogen was merged with fresh air in a chamber situated before the intake manifold, and then entered the combustion chamber from the intake manifold. Idle operation was maintained for the engine to achieve the operating temperature with each test fuel, confirming consistency in operating conditions. Data recording commenced at 60 °C engine oil temperature across all test fuels to facilitate precise comparisons. The cylinder containing hydrogen is kept at a distance throughout the experiment to avoid unintended heating from the setup. A high-frequency data collection setup was employed to link pressure signals to a computer, allowing for the recording of combustion parameters such as heat release rate and in-cylinder pressure. Emissions of NO<sub>x</sub>, CO, HC and CO<sub>2</sub> are assessed using the ATS 206 exhaust gas analyzer. Emissions testing involves two stages: first, the engine tailpipe undergoes automatic calibration and cleaning to remove any existing gases, and then the analyzer probe is employed to evaluate NO<sub>x</sub>, CO, HC and CO<sub>2</sub> levels, as referenced in [26]. Further, reference values are recorded by operating the engine with diesel fuel.



**Fig. 4.** Studied diesel engine.

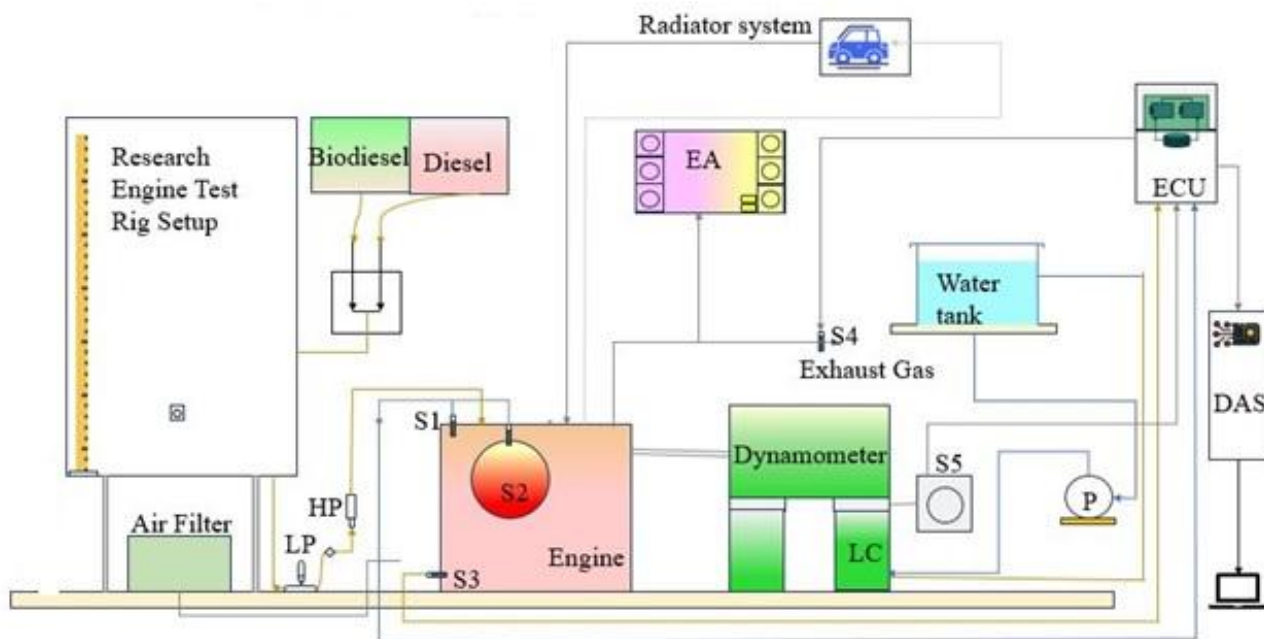


**Fig. 5.** Schematic layout of the diesel engine test unit.

|                        |                              |                                 |
|------------------------|------------------------------|---------------------------------|
| LC: Load Cell          | DAS: Data Acquisition System | EA: Emission Analyser           |
| LP: Low Pressure Pump  | P: Water Pump                | ECU: Electronic Control Unit    |
| HP: High Pressure Pump | S1: Fuel Pressure Sensor     | S2: In Cylinder Pressure Sensor |
| S3: Crank Angle Sensor | S4: Exhaust Gas Sensor       | S5: Rotary Encoder              |
| S6: Mixing Chamber     |                              |                                 |

**Table 2.** Specification of the diesel engine.

| Particulars               | Description/value                                       | Unit            |
|---------------------------|---------------------------------------------------------|-----------------|
| Engine type               | 4-S, Single cylinder, Vertical, water cooled, CI engine | -               |
| Number of cylinders       | 1                                                       | -               |
| Stroke                    | 139.7                                                   | mm              |
| Bore                      | 120                                                     | mm              |
| Cubic capacity            | 1580                                                    | cm <sup>3</sup> |
| Compression ratio         | 17.5:1                                                  | -               |
| Rated output              | 7.45                                                    | kW              |
| Rated speed               | 1500                                                    | rpm             |
| Capacity of fuel tank     | 6.5                                                     | L               |
| Fuel injection timing     | 23° BTDC                                                | -               |
| Injection pressure        | 200                                                     | bar             |
| Sump capacity of lube oil | 3.7                                                     | L               |
| Engine weight             | 150                                                     | kg              |
| Fuel Injection            | Direct injection                                        | -               |

The important performance parameters like brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) are determined using the following relations respectively.

brake thermal efficiency (BTE) are determined using the following relations respectively.

$$\text{BSFC (kg/kW h)} = \frac{\text{Mass of fuel consumption}}{\text{Brake power}} * 3600 \quad (1)$$

$$\text{BTE (\%)} = \frac{\text{Brake power (kW)}}{\text{Mass of fuel consumption} * \text{Calorific value of fuel}} * 100 \quad (2)$$

### 3.1 Uncertainty analysis

During the experimental process, variations in configuration, environmental conditions, and instrumentation introduced potential inaccuracies into the measured parameters. These inaccuracies are generally categorized as either random errors or bias (systematic) errors, each arising from distinct contributing factors. Bias errors stem from consistent deviations due to calibration offsets, misalignments, or procedural flaws, and are typically assessed through calibration techniques or comparison with historical reference data. Conversely, random errors arise from inherent variability and fluctuations in measurements, and their influence can be mitigated by increasing the number of observations or replicates. The evaluation of experimental uncertainty involves the application of standardized methodological equations, supported by data acquired through precision instruments, sensors, and computational tools. In this context, uncertainty analysis was performed by averaging the results from six independent experimental trials conducted on a specific parameter. This approach aimed to approximate the true value and facilitate comprehensive error assessment. To quantify uncertainty, several unknown error sources were determined using established parameters and mathematically derived relationships. The combined uncertainty was calculated using the square root summation rule, commonly referred to as Holman's method [26a]. This technique provides a systematic approach to consolidating individual uncertainty components, thereby yielding an overall estimation of experimental reliability.

$$U_E = \{[(\frac{\partial E}{\partial X_1})u_1]^2 + (\frac{\partial E}{\partial X_2})u_2]^2 + (\frac{\partial E}{\partial X_3})u_3]^2 + ..... + (\frac{\partial E}{\partial X_n})u_n]^2\}^{1/2} \quad (3)$$

Here, E indicates the main variable affecting all others,  $X_1$  to  $X_n$  are the experimental quantities, and the  $u_1 \dots u_n$  symbols show the uncertainty levels in the outcomes. The uncertainty percentage for, BSFC:  $\pm 0.75\%$ ; BTE:  $\pm 0.25\%$ ; EGT:  $\pm 1\%$ ; HC:  $\pm 0.25\%$ ; CO:  $\pm 0.1\%$ ; NOx:  $\pm 0.5\%$  and CO<sub>2</sub>:  $\pm 0.5\%$  is taken for error computation. Hence, the total experimental uncertainty is computed as  $\pm 1.482$ . This value aligns with previous research findings [27].

$$Total\ uncertainty = \sqrt{BSFC^2 + BTE^2 + EGT^2 + HC^2 + CO^2 + CO_2^2 + NO_x^2} \quad (4)$$

## 4. Results and discussion

### 4.1 Brake specific fuel consumption (BSFC)

The quantity of energy consumed to generate unit power is specified as the Brake specific fuel consumption (BSFC). **Fig. 6** depicts the variation in BSFC for prepared test blends with varying engine load. Whereas BSFC is found to be increased for MSB20B5TiO<sub>2</sub>100ppm by 10% in comparison to conventional diesel at full loading. The inclusion of butanol in the diesel blend leads to an increased BSFC compared to diesel alone, owing to its reduced calorific value and higher fuel demand at the same load. Further, butanol exhibits higher heat of vaporization resulting lowers the combustion temperature in cylinder [28].

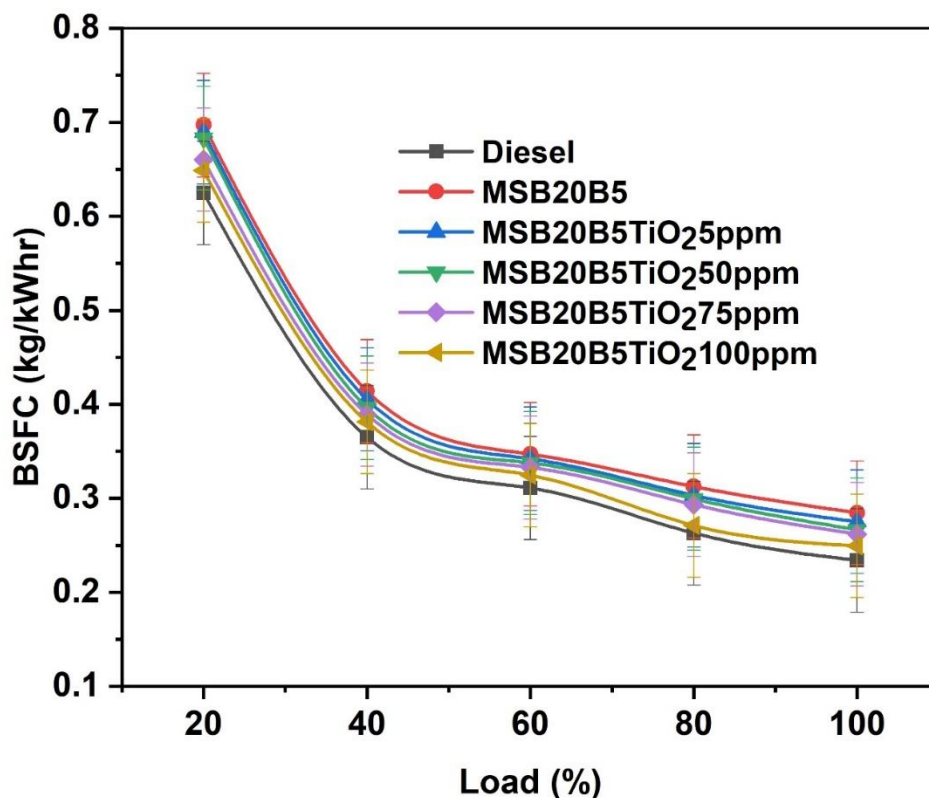


**Fig. 6.** Brake specific fuel consumption (BSFC) vs load.

The BSFC values for MSB20B5TiO<sub>2</sub> blends with 25, 50, 75, and 100 ppm TiO<sub>2</sub> concentrations were found to be lower by 3.37%, 6.39%, 8.04%, and 9.59%, respectively, relative to MSB20B5 at full load. The primary reason lies in the intense and rapid droplet breakup, known as ‘micro-explosion’, caused by the presence of butanol and TiO<sub>2</sub>, which promotes fuel evaporation and distribution, thereby enhancing TiO<sub>2</sub>’s catalytic activity [29]. Furthermore, the rich oxygen content in butanol and MSB20 promote superior combustion, which results in an increased cetane number and improved performance of the premixed fuel blend [30].

#### 4.2 Brake thermal efficiency (BTE)

Brake thermal efficiency (BTE) of a diesel engine refers to its ability to convert the chemical energy of the

test fuel into useful mechanical work, primarily influenced by the fuel's calorific value and the engine's diesel consumption rate during operation [31]. **Fig. 7** illustrates that the BTE for the test fuels improves with increasing engine load, primarily due to higher combustion rates at elevated temperatures as in [32]. At full load, the BTE for MSB20B5TiO<sub>2</sub> 100 ppm decreases by 2.05% compared to conventional diesel. Furthermore, at full load, the BTE is observed to increase by 3.23%, 6.50%, 8.19%, and 9.89% for MSB20B5TiO<sub>2</sub> 25 ppm, 50 ppm, 75 ppm, and 100 ppm blends, respectively, compared to MSB20B5. The observed effects could be attributed to the dynamic properties of the nano-catalysts blended with bio-ethanol. An increase in the concentration of metal-doped TiO<sub>2</sub> nano-additives from 25 to 100 ppm resulted in a more pronounced micro-explosion effect. This, in turn, led to a reduction in improved oxygen buffering capacity, lower fuel viscosity, ignition delay, and enhanced heating value culminating in a higher rate of combustion [33].

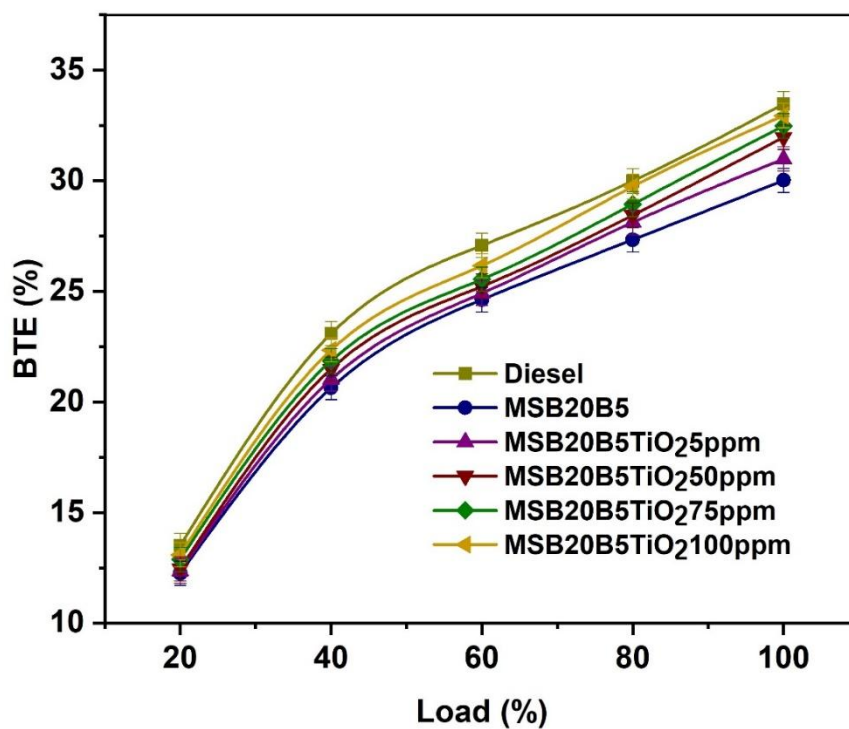


**Fig. 7.** Brake thermal efficiency (BTE) vs load

The addition of metal-doped TiO<sub>2</sub> nano-additives causes greater micro-explosion of fuel droplets, due to their high surface area-to-volume ratio. This boosts the evaporation rate and shortens the ignition delay, leading to improved combustion efficiency and higher BTE. Also, the oxygen-rich nature of bio-ethanol increases the cetane number and enhances the performance of the premixed fuel [34].

### 4.3 Exhaust gas temperature (EGT)

**Fig. 8** depicts the variation in Exhaust gas temperature (EGT) for all test fuel at different engine load. The collected findings show that EGT rises as engine load rises for all tested fuels. As the engine cylinder temperature increases, more fuel may be consumed to cope with the added load, causing the observed rise. Additionally, the higher concentration of oxygen present in MSB20B5TiO<sub>2</sub>100ppm leading more oxidation of fuel. EGT is found to be increased for MSB20B5, MSB20B5TiO<sub>2</sub>225ppm, MSB20B5TiO<sub>2</sub>250ppm, MSB20B5TiO<sub>2</sub>275ppm and MSB20B5TiO<sub>2</sub>100ppm by 3.70%, 5.55%, 7.41%, 8.79% and 10.18% respectively in comparison to conventional diesel at maximum loading as in [34a]. Nanoparticle dispersion lowers the ignition delay, increasing both exhaust enthalpy and cylinder temperature due to improved combustion uniformity. The combination of nanoparticles with biodiesel further raises exhaust temperature. Furthermore, nanoparticles promote secondary atomization or micro-explosions, leading to finer droplet breakup and more efficient combustion, elevating exhaust temperature. The study by Ge et al. [34b] revealed that blending alumina nanoparticles with biodiesel-diesel fuels caused a rise in the exhaust gas temperature in CI engines.

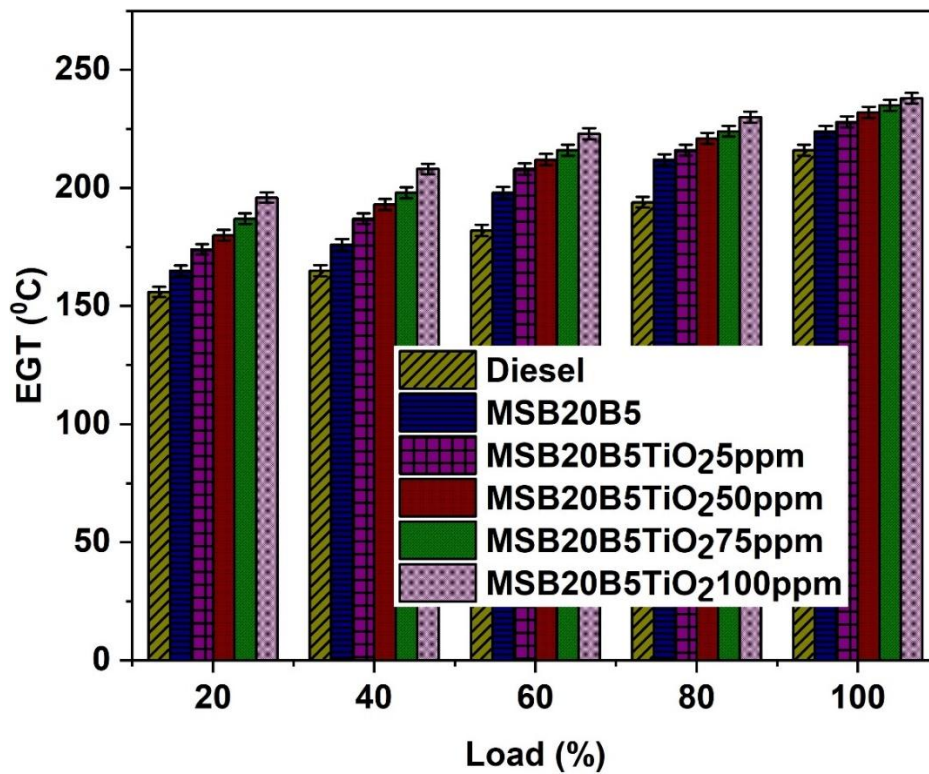


**Fig. 8.** Exhaust gas temperature (EGT) vs load

#### 4.4 NO<sub>x</sub>

Nitrogen oxides are generated from the reaction of oxygen and nitrogen during high-temperature combustion. Key factors influencing NO<sub>x</sub> formation include the concentration of local oxygen, the combustion temperature and the time the gases remain in high-temperature zones. **Fig. 9** depicts the variation in NO<sub>x</sub> emission of all test fuel increases with engine load. NO<sub>x</sub> emissions at full load were measured as 178 ppm for diesel, 195 ppm for MSB20B5, 210 ppm for MSB20B5TiO<sub>2</sub> 25 ppm, 229 ppm for MSB20B5TiO<sub>2</sub> 50 ppm, 240 ppm for MSB20B5TiO<sub>2</sub> 75 ppm, and 270 ppm for MSB20B5TiO<sub>2</sub> 100 ppm. At maximum load, NO<sub>x</sub> emissions increased by 9.55%, 17.97%, 28.65%, 34.83%, and 51.68% for MSB20B5, MSB20B5TiO<sub>2</sub> 25 ppm, 50 ppm, 75 ppm, and 100 ppm blends, respectively, in comparison to conventional diesel. The decrease in rheological properties due to addition of nano-additives promotes better atomization resulting improvement in combustion characteristics. The natural presence of oxygen promotes the oxidation rate of biodiesel, while the inclusion of TiO<sub>2</sub> nano-additives enhances in-cylinder temperature due to their high thermal conductivity. Additionally, the effect of butanol in the ternary fuel and the greater retention of thermal energy within the engine's combustion chamber contribute to improved combustion characteristics. These observations are consistent with findings reported in previous study [35].

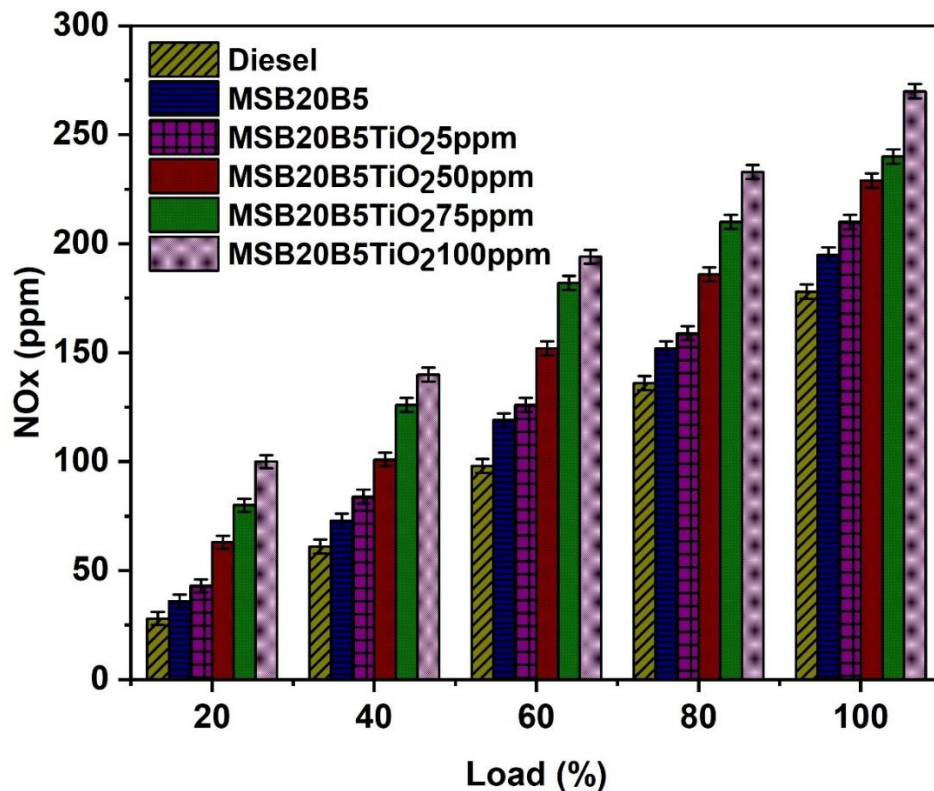


**Fig. 9.** NO<sub>x</sub> vs load.

## 4.5 CO<sub>2</sub>

The presence of CO<sub>2</sub> emissions in internal combustion engines reflects complete combustion. While CO<sub>2</sub> indicates complete combustion, it is also a major greenhouse gas with a substantial impact on climate change and global warming [36]. The effects of the all test fuel on CO<sub>2</sub> emissions under different engine loads are demonstrated in **Fig. 10**. It was observed CO<sub>2</sub> emissions increased with engine load as reported previously by [37]. MSB20B5 showed lower emissions by 3.88% in comparison to diesel. At maximum load, CO<sub>2</sub> emissions decreased by 32.25%, 35.48%, 38.71%, and 47.58% for MSB20B5TiO<sub>2</sub>25ppm, 50ppm, 75ppm, and 100ppm respectively, when compared to MSB20B5. The underlying reason could be attributed to a more complete combustion process at higher engine loads, caused by elevated in-cylinder gas temperatures. The addition of biodiesel exhibited positive impacts under varying load conditions. In particular, lower CO<sub>2</sub> emissions were recorded at high engine loads compared to mineral diesel, potentially due to the oxygen content in biodiesel and its lower carbon-to-hydrogen ratio. Additionally, These differences could stem from a trade-off between the beneficial catalytic properties of the nano-additive and its tendency to increase the oxygen content in fuel blend [38].

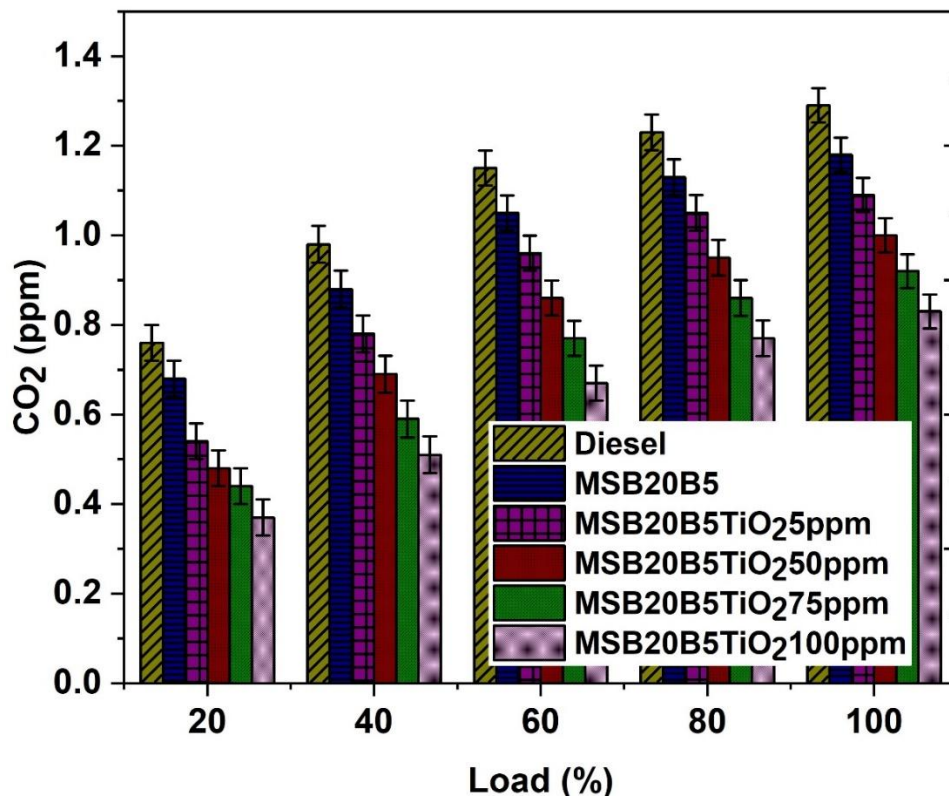


**Fig. 10.** CO<sub>2</sub> vs load

## 4.6 CO

CO formation mainly results from low oxygen availability, which limits carbon oxidation to carbon dioxide. Unburnt carbon left in the combustion chamber reacts incompletely with oxygen, producing CO. Poor fuel–air mixing and fuel-rich zones further increase CO emissions [39]. Fig. 11 illustrates the variation in CO emissions for all test fuels with engine load. Diesel yielded higher CO emissions at all loads, attributed to elevated combustion temperatures and better volumetric efficiency at low loads, enabling efficient combustion despite the absence of oxygen in the fuel blends. Biodiesel and its fuel blends produce lower CO emissions than diesel, primarily because the oxygen content in the blends supports enhanced auto-ignition characteristics during combustion in diesel engines. CO emissions were reduced by 9.88%, 25.92%, 30.86%, 37.03%, and 49.38% for MSB20B5, and MSB20B5TiO<sub>2</sub> at 25 ppm, 50 ppm, 75 ppm, and 100 ppm, respectively, compared to conventional diesel at maximum load. Experiments reveals that CO emission reduces with increasing TiO<sub>2</sub> nanoparticle concentrations in biodiesel-butanol blend for an individual load whereas increases with increasing engine load. CO emission reduction was also attributed to the presence of optimal calorific value under all loading conditions. The tested blends outperformed mineral diesel in minimizing CO, likely due to enhanced fuel atomization, superior cetane number and higher latent heat of vaporization and this reason was also supported by previous studies [40,41].

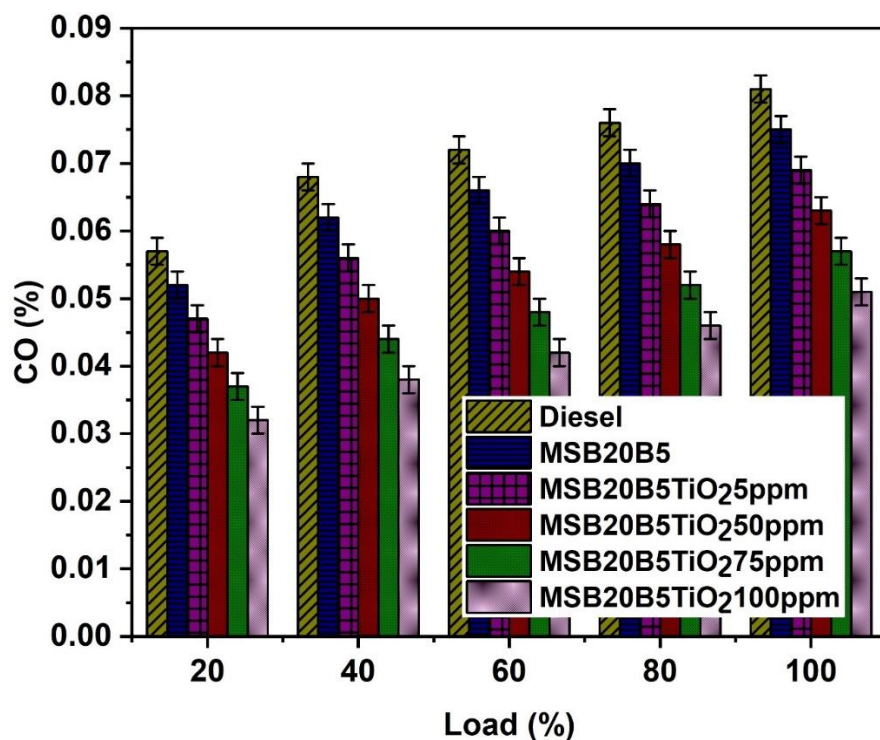


Fig. 11. CO vs load.

## 4.7 HC

Generally, reduced HC emissions may result from the oxygen content and base fuel's higher cetane number. Additional factors include a reduced quenching loss, minimal fuel losses, better combustion characteristics, and shorter ignition delay. **Fig. 12** depicts the variation of HC emission for prepared test blends and diesel with engine load. HC emissions were highest for diesel, while biodiesel blends presented lower values, attributed to their higher cetane rating and oxygen content. Ketone formation occurs during biodiesel combustion, accompanied by reduced UBHC, while diesel combustion yields no ketones [42]. HC emissions for diesel, MSB20B5, MSB20B5TiO<sub>2</sub>25ppm, MSB20B5TiO<sub>2</sub>50ppm, MSB20B5TiO<sub>2</sub>75ppm and MSB20B5TiO<sub>2</sub>100ppm were recorded as 165, 151, 142, 133, 124 and 117 ppm respectively at maximum load. Fuel atomization, driven by surface tension, density, and viscosity, creates rich zones in the engine's combustion chamber. TiO<sub>2</sub> concentrations in the blend help notably reduce HC emissions. Studies have shown that blending biodiesel with diesel fuel generally mitigates HC emissions by improving the oxidation of unburned hydrocarbons, due to biodiesel's inherent oxygen content [43]. Contrary to expectations, the inclusion of biodiesel and butanol resulted in lower in-cylinder temperatures due to their high vaporization heat.

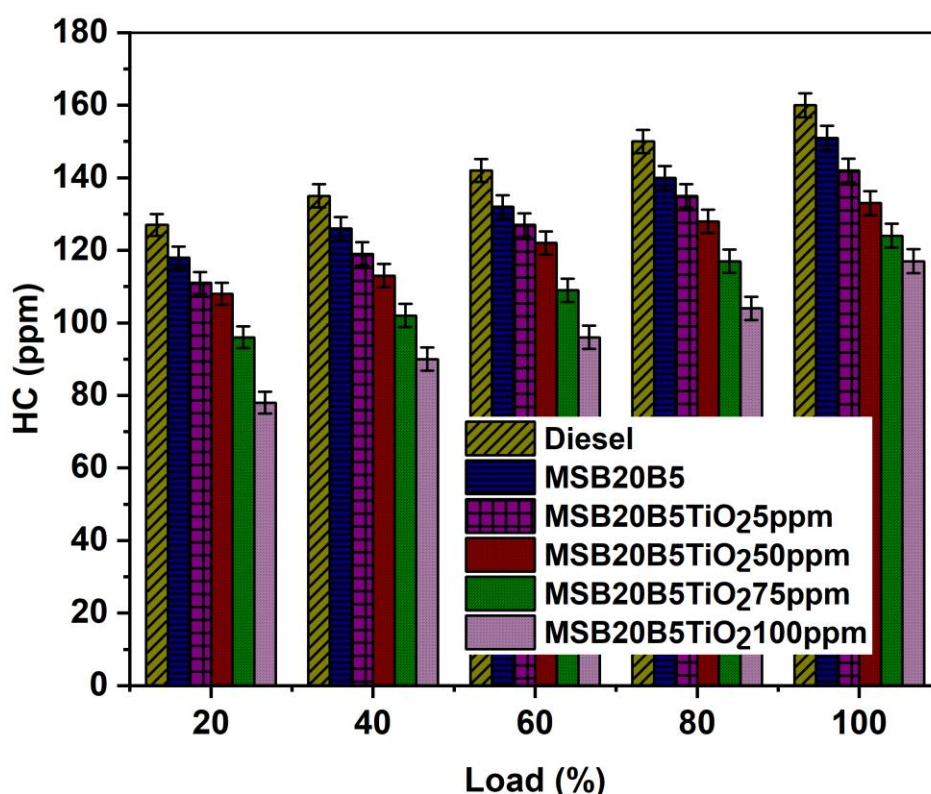


**Fig. 12** HC. vs load.

The comparison of performance and emissions of the present study with the previous studies are given in Table 3.

Table. 3 Comparative analysis on performance and emissions of the present study with previous studies.

| Engine specification              | Operating conditions          | Oils      | Performance |          | Emission |       |                     |                     |
|-----------------------------------|-------------------------------|-----------|-------------|----------|----------|-------|---------------------|---------------------|
|                                   |                               |           | BTE(%)      | BSFC (%) | CO(%)    | HC(%) | NO <sub>x</sub> (%) | CO <sub>2</sub> (%) |
| 4S, 1C, CI, WC, RS:1000RP M, [44] | Load: 25%, 50%, 75%, 100%     | B5        | 12.3↓       | 14.6↑    | 18.2↓    | 20↑   | 7.4↓                | 5.7↓                |
|                                   |                               | B5W3      | 29.2↓       | 41.7↑    | 118.2↑   | 145↑  | 2.1↓                | 4.7↓                |
|                                   |                               | B5W3(CNP3 | 7.7↑        | 2.1↓     | 113.6↑   | 260↑  | 4.2↓                | 21.2↓               |
|                                   |                               | 8)        | 7.7↓        | 14.6↑    | 168.2↑   | 270↑  | 7.4↓                | 21.2↓               |
|                                   |                               | B5W3(CNP7 | 1.5↓        | 4.2↑     | 109.1↑   | 340↑  | 5.3↑                | 24.5↓               |
| 4S, 1C, CI, WC, RS:2200RP M,      | Load: 10%, 30%, 50%, 70%, 90% | E15       | 1.0↑        | 4.6↑     | 10.1↓    | 12.2↑ | 4.4↑                | -                   |
|                                   |                               | EGO25     | 2.0↑        | 2.7↑     | 16.8↓    | 2.4↓  | 12.4↑               |                     |
|                                   |                               | EGO100    | 3.0↑        | 1.5↑     | 19.7↓    | 8.5↓  | 20.4↑               |                     |
|                                   |                               | EMGO25    | 1.4↑        | 2.7↑     | 23.2↓    | 7.8↓  | 6.0↑                |                     |
|                                   |                               | EMGO100   | 3.1↑        | 1.5↑     | 25.9↓    | 21.9↓ | 16.7↑               |                     |
|                                   |                               | ECNT25    | 1.4↑        | 2.7↑     | 16.0↓    | 2.4↓  | 5.5↑                |                     |
|                                   |                               | ECNT100   | 1.2↑        | 1.7↑     | 21.7↓    | 26.8↓ | 12.4↑               |                     |

|                                                                         |                                                      |                                                           |                                      |                              |                                          |                                         |                                         |   |
|-------------------------------------------------------------------------|------------------------------------------------------|-----------------------------------------------------------|--------------------------------------|------------------------------|------------------------------------------|-----------------------------------------|-----------------------------------------|---|
| RP:12.<br>1kW<br>[45]                                                   |                                                      |                                                           |                                      |                              |                                          |                                         |                                         |   |
| 4S,<br>1C,<br>CI,<br>AC,<br>RS:15<br>00RP<br>M,<br>RP:5.2<br>kW<br>[29] | Load: 0%,<br>25%, 50%,<br>75%, 100%                  | Blend2<br>Blend3<br>Blend4<br>Blend5<br>Blend6            | 0.2↓<br>0.3↓<br>4.7↓<br>3.9↓<br>0.1↓ | -                            | 27.1↓<br>11.0↓<br>4.4↓<br>37.0↓<br>51.9↓ | 15.0↓<br>11.2↓<br>2.5↓<br>8.7↓<br>26.2↓ | 8.1↑<br>20.0↑<br>1.5↑<br>39.3↑<br>44.4↑ | - |
| 4S,<br>1C,<br>CI,<br>RS:15<br>00RP<br>M,<br>RP:3.5<br>Kw<br>[46]        | BMEP:<br>1.03bar,<br>2.05bar,<br>3.09bar,<br>4.14bar | CDF15PWB<br>CDF30PWB<br>CDF30PWB<br>CUO<br>CDF30PWB<br>CN | 2.7↑<br>5.5↑<br>8.6↑<br>10.6↑        | 2.4↓<br>5.1↓<br>7.5↓<br>9.9↓ | 5.0↓<br>5.0↓<br>12.5↓<br>17.5↓           | 10.0↓<br>10.0↓<br>20.0↓<br>30.0↓        | 3.8↑<br>5.7↑<br>8.0↓<br>3.8↓            | - |

|                                                                                 |                                     |                       |       |        |        |         |        |        |
|---------------------------------------------------------------------------------|-------------------------------------|-----------------------|-------|--------|--------|---------|--------|--------|
| 4S,<br>1C,<br>CI,<br>RS:15<br>00RP<br>M,<br>RP:7.4<br>5kW<br>[Present<br>study] | Load: 20%,<br>40%, 60%,<br>80%, 100 | MSB20B5,              | 10.3↓ | 21.66↑ | 9.88 ↓ | 8.49 ↓  | 9.55 ↑ | 8.87 ↓ |
|                                                                                 |                                     | MSB20B5Ti             | 7.44↓ | 17.56↑ | 25.92↓ | 13.94 ↓ | 17.97↑ | 34.92↓ |
|                                                                                 |                                     | O <sub>2</sub> 25ppm, |       |        |        |         |        |        |
|                                                                                 |                                     | MSB20B5Ti             | 4.51↓ | 13.88↑ | 30.86↓ | 19.39 ↓ | 28.65↑ | 37.66↓ |
|                                                                                 |                                     | O <sub>2</sub> 50ppm, |       |        |        |         |        |        |
| M,<br>RP:7.4<br>5kW<br>[Present<br>study]                                       |                                     | MSB20B5Ti             | 2.98↓ | 11.88↑ | 37.03↓ | 24.85 ↓ | 34.83↑ | 41.13↓ |
|                                                                                 |                                     | O <sub>2</sub> 75ppm  |       |        |        |         |        |        |
|                                                                                 |                                     | MSB20B5Ti             | 1.58↓ | 6.58↑  | 49.38↓ | 29.91 ↓ | 51.68↑ | 49.36↓ |
| 1C,<br>AC,<br>CI,<br>RS:36<br>00RP<br>M,<br>[47]                                | BP: 0.98kW<br>to 3.92kW             | C20                   | 1.2↑  | 1.5↑   | 6.7 ↓  | 4.3↑    | 4.8↑   | 2.8↓   |
|                                                                                 |                                     | C20Mo50               | 2.5↑  | 1.5↓   | 10.2↓  | 4.9↓    | 6.2↓   | 7.0↓   |
|                                                                                 |                                     | C20Mo100              | 5.0↑  | 4.4↓   | 13.3↓  | 8.5↓    | 9.1↓   | 10.3↓  |
|                                                                                 |                                     | C20Ba50               | 6.3↑  | 7.3↓   | 20.0↓  | 12.2↓   | 11.5↓  | 12.5↓  |
|                                                                                 |                                     | C20Ba100              | 7.2↑  | 9.4↓   | 22.7↓  | 14.0↓   | 13.3↓  | 19.0↓  |

## 5. Conclusions

The present study confirms the effectiveness of TiO<sub>2</sub> nano-additives (25–100 ppm) in ternary fuel blends for use in diesel engines. The first test involved operating the diesel engine with biodiesel, diesel, and butanol fuels. Results demonstrated improved performance using ternary fuel with TiO<sub>2</sub> (MSB20B5TiO<sub>2</sub>25ppm, MSB20B5TiO<sub>2</sub>50ppm, MSB20B5TiO<sub>2</sub>75ppm and MSB20B5TiO<sub>2</sub>100ppm). The addition of 25–100 ppm TiO<sub>2</sub> in ternary fuel enhances engine performance and reduces emissions. Overall, TiO<sub>2</sub> nano-additives in ternary fuel improved BTE near diesel levels, reduced BSFC, lowered smoke, CO, UBHC, and enhanced

NO<sub>x</sub> at peak load. The following points summarize the research work:

- ❖ MSB20B5TiO<sub>2</sub>100ppm delivered better BTE and lower BSFC than other blends, as a result of 100 ppm TiO<sub>2</sub> nano-additives improving oxygen levels and bioethanol contributing to more efficient combustion.
- ❖ At peak load, the MSB20B5TiO<sub>2</sub>100ppm blend exhibited lower CO, HC, and CO<sub>2</sub> emissions than conventional diesel, attributed to the optimized mixture of butanol, biodiesel, and TiO<sub>2</sub> nanoparticles that improved fuel combustion characteristics due to oxygen concentration.
- ❖ A higher NO<sub>x</sub> emission was recorded for all blends compared to diesel at peak load, mainly due to increase in-cylinder temperature and improved oxygen concentration from the high loading of TiO<sub>2</sub> nano additives

It was deduced from the engine results that the ternary fuel with 100 ppm TiO<sub>2</sub> is a strong candidate to replace diesel while supporting global energy sustainability. Despite its advantages, NO<sub>x</sub> emissions were higher than those in conventional diesel, suggesting the need for emission control methods such as EGR systems, bio-nano emulsified fuels, oxidation enhancers, or water-based emulsions

#### **Declarations Conflict of interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### **Funding Declaration**

There is no funding for this study.

#### **Availability of Data and Materials**

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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