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Effect of titanium dioxide nanoparticle concentration on the performance and emissions of a common rail direct injection engine with jute oil mahua ester biodiesel

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ABSTRACT

Research into sustainable and alternative fuel sources for internal combustion engines has accelerated due to ecological concerns and the reduction of fossil fuels. Common rail direct injection (CRDI) diesel engine running on jute oil mahua ester (JOME) biodiesel with titanium dioxide (TiO_2) nano-additive is used to study the performance characteristics and emissions. Biodiesel derived from jute oil, a renewable and biodegradable source, was blended with varying concentrations of TiO_2 nanoparticles () to augment the efficiency of combustion and reduce emissions. Engine tests were conducted at different loads (0, 25, 50, 75, 100%) to evaluate brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and pollutants such as nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons (HC), and smoke opacity. Results indicated that the addition of TiO_2 nanoparticles improved combustion performance due to their catalytic properties and oxygen buffering capacity, leading to enhanced BTE and a notable decrease in CO and unburned hydrocarbons. However, a small rise in NO_x emissions was detected, attributed to higher engine temperatures. Among the tested concentrations, B20+T50 ppm TiO_2 emerged as the optimal dosage, balancing improved performance and reduced emissions without causing injector clogging or adverse effects. Overall, the usage of TiO_2 nanoparticles in jute biodiesel (B20 blend) presents a promising pathway toward cleaner and more efficient engine operation. This aligns with global efforts to diminish greenhouse gas emissions and encourage sustainable energy solutions.

Keywords: emissions, performance, CRDI engine, jute oil, biodiesel, nanoparticle, environmental.

INTRODUCTION

The increased global demand for energy, exhaustion of fossil fuels and escalating environmental concerns, has driven a significant shift toward alternative and renewable energy sources (Ansari et al., 2023). Among various options, biodiesel has emerged as a feasible alternate for conventional diesel due to its renewable nature, biodegradability, and capacity to reduce greenhouse gas emissions (Borthakur, 2025). Vegetable oils, especially non-edible ones such as jute oil, offer a promising feedstock for biodiesel production, as they do not compete with food resources and can be cultivated on marginal lands (Rao et al., 2023).

Jute oil biodiesel possesses properties comparable to diesel fuel but typically suffers from drawbacks such as higher viscosity, lower calorific value (CV), and incomplete combustion, which can adversely disrupt the performance of engine and emissions. To overcome these limitations, the use of fuel additives, particularly metal oxide nanoparticles, has gained attention (Fayad et. al. 2023). Among them, titanium dioxide (TiO_2) nanoparticles have demonstrated significant potential due to their catalytic activity, better thermal conductivity, and ability to release oxygen during combustion, leading to better air-fuel mixing and improved combustion efficiency (Gowthaman et al., 2024).

Common rail direct injection (CRDI) engines, known for their precise fuel injection control and high-pressure atomization, are ideal platforms for evaluating the effects of biodiesel-nanoparticle blends (Fayad et al., 2023). Integrating TiO_2 nanoparticles into jute oil biodiesel in CRDI engines may provide a synergistic effect – optimizing combustion while minimizing harmful emissions.

The biodiesel blends with nano-additives have garnered increasing attention as a promising approach to augment the performance and emissions of compression ignition (CI) engines while addressing environmental concerns (Borthakur, 2025). Various nanoparticles, including titanium dioxide (TiO_2), cerium oxide (CeO_2), zinc oxide (ZnO), and alumina (Al_2O_3), have been explored for their catalytic and oxygen-buffering properties, which contribute to better performance and less exhaust emissions (Zheng & Cho 2024).

Ansari et al. (2023) examined the impact of biodiesel-nanoparticle blends on engine characteristics and noise emissions, reporting enhanced combustion and decreased acoustic emissions. Arockiasamy and Anand (2015) also demonstrated enhanced BTE and reduced CO and HC emissions with nanoparticle-blended jatropha biodiesel.

Review articles by Mahgoub (2023), Jin et al. (2023), and Zheng and Cho (2024) have comprehensively assessed the role of nano-additives in biodiesel engines. These reviews confirm that nanoparticles like TiO_2 improve fuel atomization and oxidation processes, thereby increasing engine efficiency and decreasing emissions. They also emphasize the importance of optimizing nanoparticle concentration to avoid adverse effects such as injector fouling or increased nitrogen oxides (NO_x) due to elevated combustion temperatures.

The influence of nanoparticle size on performance was studied by Dinesha et al. (2021), who found that smaller CeO_2 particles led to more efficient combustion and lower emissions. Elkelawy et al. (2023) and Lv et al. (2022) highlighted TiO_2's ability to act as an oxygen donor and soot oxidizer, significantly improving combustion efficiency. Similarly, Fayad et al. (2022) and Fayad et al. (2023) presented that TiO_2 nanoparticles, particularly in combination with exhaust gas recirculation (EGR), could effectively reduce soot and NO_x emissions in CRDI engines.

Razzaq et al. (2023) applied response surface methodology to optimize TiO_2 concentration in waste cooking oil (WCO) biodiesel blends and stated enhancements in BTE and emission reduction. Rao et al. (2023), in their study of jute oil biodiesel blended with CeO_2 nanoparticles, demonstrated the potential of jute oil as a viable biodiesel feedstock, showing positive effects on both performance and emissions.

Other studies have explored alternative nanoparticles. Gowthaman et al. (2024) examined ZnO nanoparticles with lemongrass biodiesel, and Özgören et al. (2025) studied carbon quantum dots with canola biodiesel, both reporting improved combustion characteristics and reduced emissions. Renish and Selvam (2024) found similar benefits with bio-waste-derived nanoparticles.

Le et al. (2024) and Singh et al. (2023) presented broader sustainability insights, emphasizing the potential of nanotechnology-based biodiesel as a renewable and cleaner alternative to fossil diesel. Their assessments underline the importance of balancing performance improvements with cost-effectiveness and environmental impact.

Further, Sharma et al. (2023) and Reddy et al. (2021) established that the use of nano-additives in blends of biodiesel significantly reduces harmful emissions when carefully dosed and well dispersed. Sudarsanam et al. (2024), focusing on ternary blends in CRDI engines, reported that alumina nano-additives contributed to stable combustion and decreased pollutant formation.

While numerous studies have established the efficacy of nanoparticles, particularly TiO_2, in enhancing biodiesel combustion and reducing emissions, limited research has specifically addressed their application in jute oil biodiesel for CRDI engines. The present study focuses on the effects of varying concentrations of TiO_2 nanoparticles on performance and emission outcomes, contributing to the environmentally sustainable engine technologies.

The present study examines the effect of TiO_2 nanoparticle concentration on the emissions and performance traits of a CRDI engine running on jute oil biodiesel. Key factors such as brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and smoke opacity emission levels are the focus of the study. The focus is on assessing the possible trade-offs and environmental advantages of burning biodiesel augmented by nanoparticles, with the ultimate objective of advancing cleaner and more sustainable engine technologies.

MATERIALS AND METHODS

Jute oil biodiesel was produced via a base-catalysed transesterification process with methanol and potassium hydroxide (KOH) as a catalyst. The resultant biodiesel was filtered and characterized as per ASTM D6751 standards to ensure compatibility with engine testing. TiO_2 nanoparticles of average particle size ~30 nm and >99% purity was procured from nanolabs, India. Three nanoparticle concentrations (25 ppm, 50 ppm, and 100 ppm) were dispersed into the biodiesel using a probe-type ultrasonic sonicator (frequency = 20 kHz) for 30 minutes to ensure uniform suspension. A magnetic stirrer was used to maintain stability during storage. Properties of the fuels of different types are presented in Table 1.

Experiments were performed using a 4-s, single-cylinder, water-cooled CRDI diesel engine equipped with electronic fuel injection and ECU-controlled fuel mapping. The specifications of the engine are listed in Table 2.

Figure 1 shows a laboratory stand consists of main engine, dynamometer, fuel injection system,

Table 1. Properties of fuels used Diesel engine

Fuel sample	Calorific value (kJ/kg)	Cetane number	Viscosity (cSt)	Density (kg/m^3)	Flash point (°C)	Fire point (°C)
D100+B0	44,000	51	3.02	828	53	59
B20	40,775	53	3.91	849	100	110
B20+T25	40,960	54	4.02	850	102	112
B20+T50	41,163	55	4.12	851	104	114
B20+T100	41,275	56	4.25	852	105	115

Note: D100+B0 (pure diesel), B20 (diesel 80% and JOME bio diesel 20%), B20+T25 (B20 blend with 25 ppm titanium oxide), B20+T50 (B20 blend with 50 ppm titanium oxide), B20+T100 (B20 blend with 100 ppm titanium oxide).

Table 2. Specifications of CRDI engine

Parameter	Value
Engine type	Single-cylinder, CRDI
Power	5.2 kW at 1500 rpm
Compression ratio	17.5:1
Bore and stroke	87.5 mm × 110 mm
Injection pressure	600 bar
Cooling system	Water-cooled
Dynamometer	Load cell type

Figure 1. Pictorial representation of CRDI engine experimental test rig

control and measurement panel, display units, fuel consumption measurement system, manometer and flow meter, data acquisition system. Engine is a single-cylinder CRDI diesel engine. Dynamometer is used to apply variable mechanical load on the engine and measure torque output. It helps analyze performance under different loading conditions. The CRDI setup uses high-pressure injectors fed by a common rail, controlled electronically for precise fuel delivery. Control and measurement panel is used to start or stop the engine, to set loading conditions, to monitor revolutions per minute, torque, and temperatures. Digital display units provide real-time measurements such as speed, load, fuel consumption, etc. Fuel consumption measurement unit measures the volume of fuel consumed over time, typically used to calculate brake specific fuel consumption. Valves are used to isolate and measure fuel consumption during specific test durations. Manometer and flow meter are used to measure air intake or exhaust pressure and sometimes air flow rate for air-fuel ratio analysis.

Experiments

Figure 2 presents a workflow of the experimental procedure for evaluating the outcome of TiO_2 nano-additives in biodiesel on engine parameters using a CRDI engine test rig. The process begins with blending a measured quantity of TiO_2 nanoparticles into B20 biodiesel blend. The mixture undergoes magnetic stirring, ensuring initial uniform distribution of nanoparticles in the fuel medium. This step typically lasts several minutes at a controlled temperature. Following stirring, the blend is subjected to ultrasonication. High-frequency sound waves further break down nanoparticle clusters, achieving stable and homogeneous suspension of TiO_2 particles in the biodiesel. The nanoadditive biodiesel blend is then used as a fuel in a CRDI engine experimental test rig. The engine is operated at different load conditions to analyze performance and emission characteristics. The results of the engine tests are illustrated using graphs like BTE, BSFC, emissions such as CO, NO_x, HC, Smoke opacity with respect to engine loading.

RESULTS AND DISCUSSION

Figure 3 represents the variation of BTE with respect to engine load (%) for different fuel blends, including:

- Diesel
- B20 (20% biodiesel + 80% diesel),
- B20 + T25 (B20 with 25 pp TiO_2 nanoparticles),
- B20 + T50 (B20 with 50 ppm TiO_2),
- B20 + T100 (B20 with 100 ppm TiO_2),

BTE increases with increase in engine load for all types of fuel. This is expected, as at higher loads, the engine operates more efficiently with good fuel-to-air mixing and neat combustion. B20 consistently shows lower BTE than diesel, which is typical because biodiesel has lower calorific value, higher viscosity, slightly slower combustion. All nano-additive blends (B20 + T25, T50,

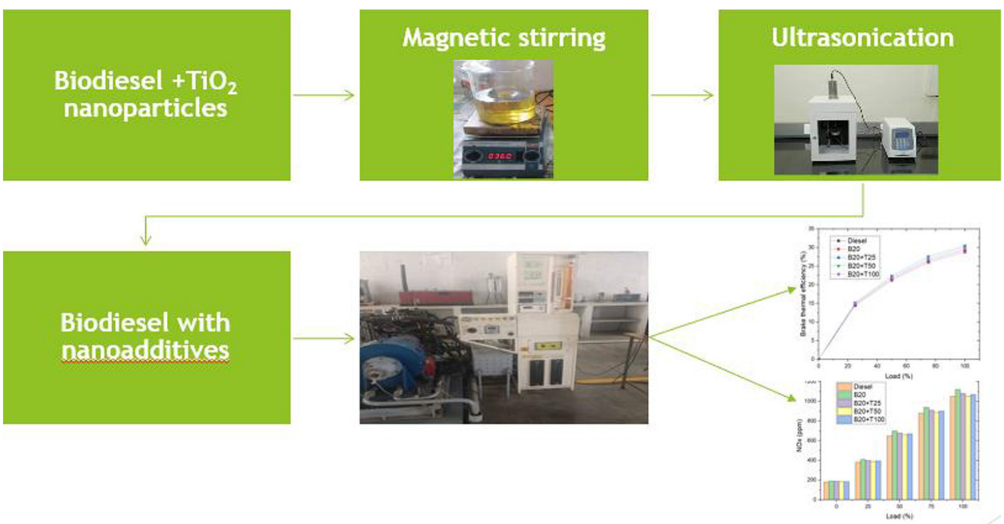

Figure 2. Sequential steps in the methodology this research

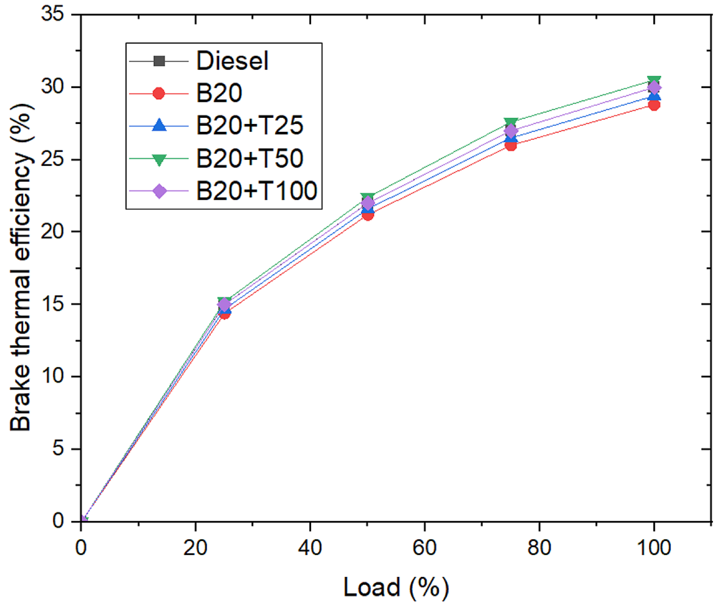

Figure 3. Brake thermal efficiency with change in engine load

T100) show improved BTE compared to plain B20. Among them, B20 + T50 shows the highest BTE at all load conditions, indicating that 50 ppm TiO_2 is the optimal concentration. B20 + T25 and B20 + T100 also show improvement over B20, but not as significant as T50. Here, TiO_2 nanoparticles act as combustion catalysts. They enhance atomization, promote better mixing of fuel and air, and improve combustion efficiency. They also help in reducing ignition delay and ensure more complete combustion. At 50 ppm, there's a balanced catalytic effect without causing issues like fuel line clogging or agglomeration. At 100 ppm (T100), the performance slightly drops, possibly due to excessive nanoparticles leading to incomplete mixing or injector fouling.

Variation of BSFC with engine load (%) for various types of fuels is shown in Figure 4. It is identified that for all fuel blends, BSFC decreases as the load increases. At higher loads, engines operate more efficiently with better combustion and power output, leading to lower BSFC. B20 shows a slightly higher BSFC than diesel at all load levels. This is occurred due to higher viscosity,

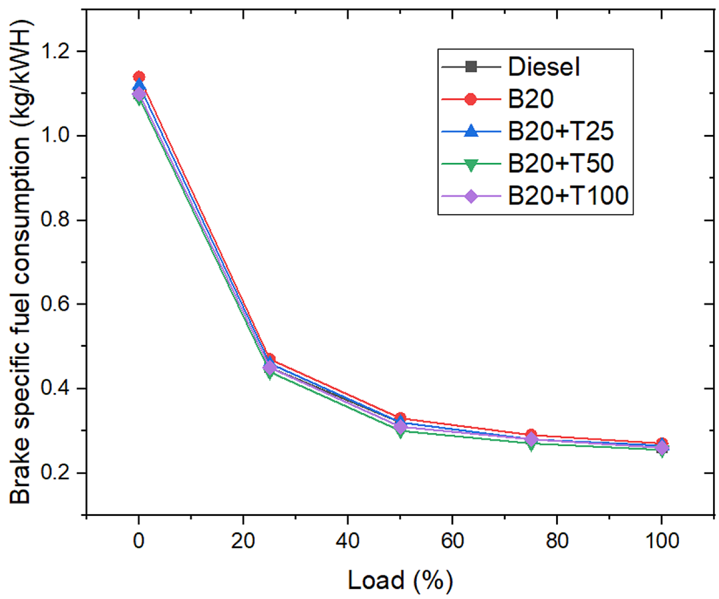

Figure 4. Brake specific fuel consumption with change in engine load

lower calorific value of biodiesel which disturbs spray patterns and efficiency of combustion. Addition of TiO_2 nanoparticles to B20 reduces BSFC compared to plain B20. Among them, B20 + T50 consistently gives the lowest BSFC, indicating optimal combustion enhancement at this concentration. B20 + T25 and B20 + T100 also show improvement, but the effect of T50 is most prominent. Since biodiesel contains oxygen, it helps in better combustion but needs more fuel volume to produce the same power due to its lower energy content. Catalytic behavior of TiO_2 helps in better fuel atomization, faster and neat combustion, reduced ignition delay. As a result, less fuel is spent per unit of power output, reducing BSFC. TiO_2 at 50 ppm is observed to be the most effective, likely providing the best balance of dispersion, surface area, and combustion enhancement. At 100 ppm, a slight increase in BSFC may occur due to agglomeration or saturation, reducing the effectiveness of the nanoparticles.

Variation of CO emission (%) with respect to engine load (%) for different types of fuels is represented in Figure 5. CO emissions decline as load rises for all types of fuels. This is because higher loads result in higher combustion temperatures, leading to more neat combustion and less CO formation. At all loads, B20 emits slightly more CO than diesel. Biodiesel's lower volatility and higher viscosity can cause incomplete combustion, increasing CO. Adding TiO_2 nanoparticles to B20 reduces CO emissions at all loads. Among the nano-blends, B20 + T50 consistently shows the lowest CO emissions. B20 + T25 and B20 + T100 also show reductions but are slightly less effective than B20 + T50. CO is formed due to incomplete combustion when there's no sufficient oxygen or poor mixing of air and fuel. TiO_2 nanoparticles act as oxidation catalysts. They promote better air-fuel mixing and enhance combustion efficiency. As a result, more CO is converted into CO_2, leading to a drop in CO emissions. 50 ppm appears to provide the best dispersion and catalytic action. Higher concentrations (100 ppm) may result in agglomeration, reducing effectiveness. Lower concentrations (25 ppm) may not be sufficient to catalyze combustion optimally.

Variation of hydrocarbon (HC) emissions (ppm) with load (%) for different types of fuel is shown in Figure 6 HC emissions are developed as the result of incomplete combustion where some fuel remains unburnt. This happens due to poor atomization, low combustion temperatures, or quenching in cold zones inside the cylinder. HC emissions decrease with load across all fuel types, HC emissions reduce as engine load increases. At higher loads, combustion becomes more complete due to increased temperature and pressure, resulting in fewer unburnt hydrocarbons.

B20 emits more HC than diesel at all loads. This is likely due to higher viscosity and lower volatility of biodiesel, leading to incomplete combustion and formation of unburned hydrocarbons. Addition of TiO_2 nanoparticles to B20 significantly reduces HC emissions at all loads. Among the nano-blends, B20 + T50 and B20 + T100 exhibit the

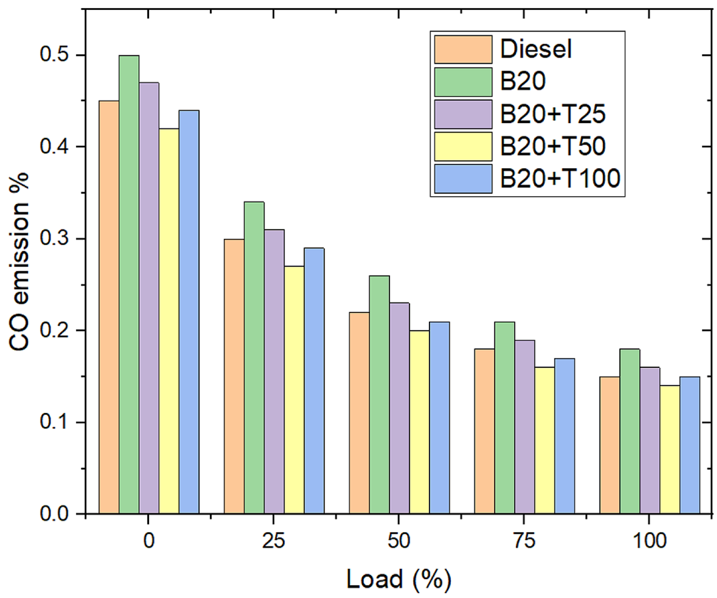

Figure 5. CO emissions with change in load

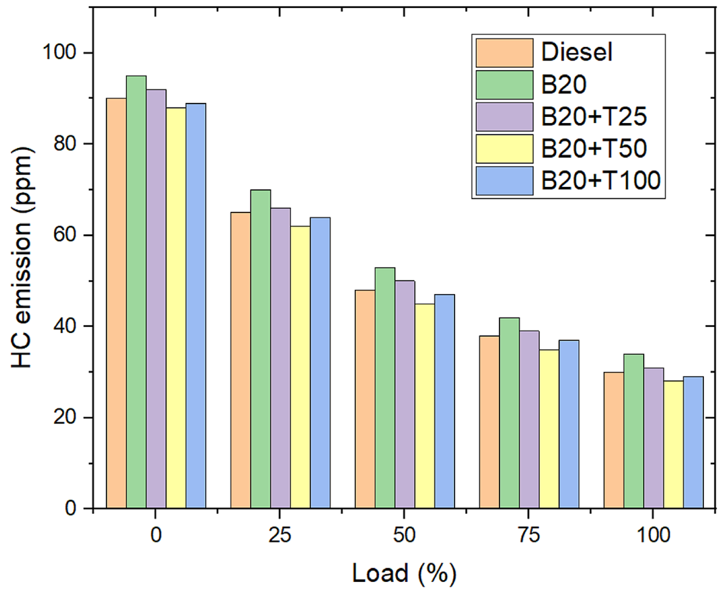

Figure 6. HC emissions with change in engine load

lowest HC emissions, especially at higher loads. TiO_2 nanoparticles enhance combustion by acting as oxidation catalysts. They improve fuel-air mixing and promote complete burning, reducing the amount of unburnt hydrocarbons. Higher concentration (50–100 ppm) appears to improve this catalytic action, but performance may plateau beyond a certain level (as seen with B20 + T100).

Figure 7 illustrates the nitrogen oxides emissions in ppm with varying engine load (%) for different fuels. NO_x emissions increase with load for all fuels, NO_x emissions rise steadily as engine load increases. This is due to higher in-cylinder temperature and excess oxygen, which promote the formation of thermal NOx during combustion. B20 consistently emits higher NO_x than diesel, particularly at higher loads (75% and 100%). Biodiesel contains oxygen molecules in its structure, which enhances combustion but also raises combustion temperature, increasing NO_x. Adding TiO_2 to B20 slightly reduces NO_x emissions compared to plain B20. Among them, B20 + T50 and B20 + T100 blends exhibit notable reductions, especially at higher loads. However, all B20-based fuels still show higher NO_x than diesel at maximum load. At higher loads, more fuel is injected, leading to

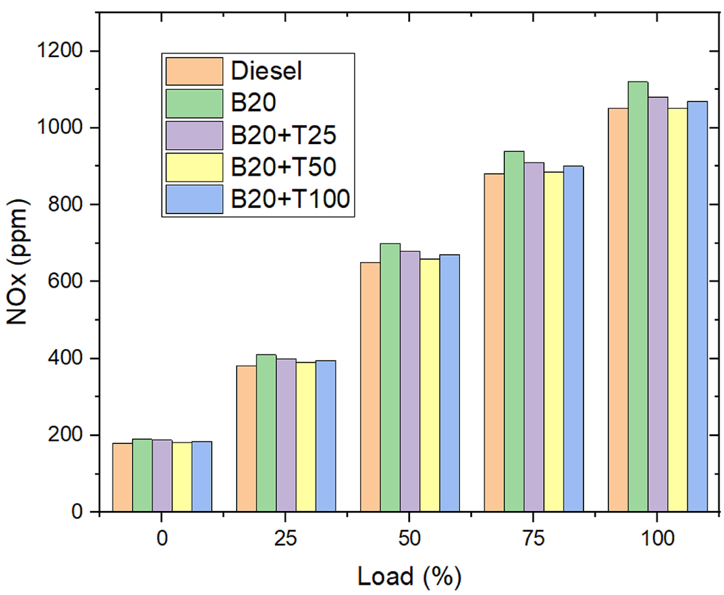

Figure 7. NO_x emissions with change in engine load

higher pressure and temperature. High temperature facilitates nitrogen oxidation, producing NO_x. Biodiesel's oxygen content enhances combustion but also increases peak flame temperature, which is a critical factor in NO_x formation. This is why B20 shows higher NO_x than diesel despite being a cleaner fuel in other respects. TiO_2 has thermal stability and oxygen storage/release capacity. It helps in moderating combustion temperature slightly by promoting a more uniform burn, potentially reducing localized hotspots responsible for NO_x. Still, the reduction in NO_x is limited, especially at very high loads.

Smoke opacity versus load for different fuel blends is represented in Figure 8. For all fuels, smoke opacity rises with increasing engine load. This is expected, as more fuel is injected at higher loads, and combustion becomes richer, increasing soot formation. At all load levels, pure diesel consistently shows the highest smoke opacity, especially at 75% and 100% load. At full load, diesel reaches above 35%, indicating significant soot emissions. B20 emits less smoke than diesel at all loads. This is due to the oxygen content in biodiesel, which improves combustion efficiency and reduces soot generation. Adding TiO_2 further reduces smoke opacity. B20 + T100 shows the lowest smoke levels across all loads. This suggests TiO_2 helps catalyze more complete combustion and possibly oxidizes soot particles. Smoke capacity is a direct indicator of particulate matter (PM) or soot in exhaust gases. Biodiesel reduces smoke due to its higher oxygen content and absence of aromatic compounds. TiO_2 nanoparticles act as combustion catalysts enhance oxygen availability at a micro level, promote oxidation of soot, improve mixing and combustion homogeneity.

Environmental effects

Using TiO_2 (titanium dioxide) nanoadditives in fuel blends like B20 (biodiesel 20%) has several notable environmental effects, especially in terms of emission reduction and combustion efficiency.

Positive environmental effects

TiO_2 nanoparticles promote more complete combustion of fuel. This reduces the formation of CO, a toxic and partially oxidized by-product. Cleaner exhaust helps reduce air toxicity and the impact on human health. Incomplete combustion results in unburned hydrocarbons. TiO_2, due to its oxidizing and catalytic properties, aids in breaking down HC molecules. This helps in lowering ground-level ozone formation and photochemical smog. TiO_2 helps oxidize soot and reduces particulate matter. Reducing soot leads to better air quality, less respiratory irritation, lower climate-forcing black carbon in the atmosphere.

Potential environmental concerns

While TiO_2 shows benefits, its nanoparticle form raises some emerging environmental concerns. If released into the atmosphere or water bodies, TiO_2 nanoparticles may have toxic

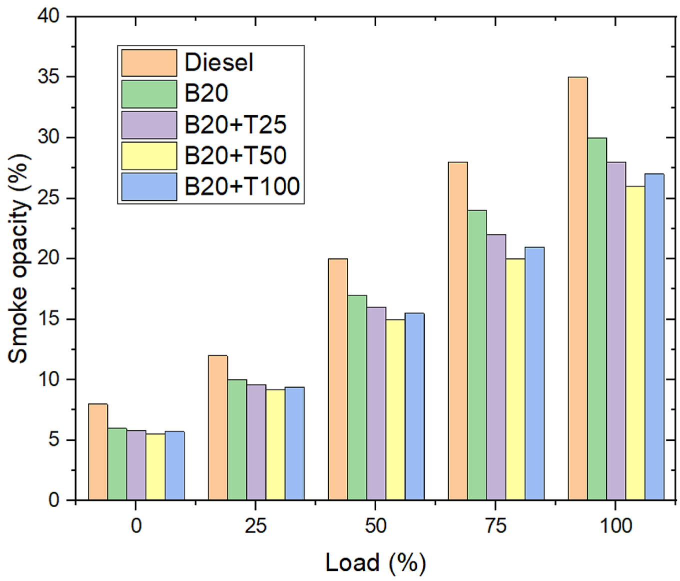

Figure 8. Smoke opacity with load variation

effects on aquatic life and soil microorganisms. Their small size makes them biologically reactive and potentially bioaccumulative. There are concerns about accumulation in the environment if nanoparticles are not fully consumed or captured. Long-term environmental behavior (e.g., mobility in soil/water) is still being researched. Inhalation or ingestion of free TiO_2 nanoparticles can potentially cause lung inflammation or other health issues, though studies are ongoing.

CONCLUSIONS

The dispersion of TiO_2 nanoparticles into B20 blend of biodiesel significantly improved the BTE. Among all blends, B20 + 50 ppm TiO_2 exhibited the highest improvement, indicating enhanced combustion due to the catalytic action of nanoparticles. The BSFC decreased with the addition of TiO_2. This suggests that the presence of titania nanoparticles improves the efficiency of combustion, leading to better energy extraction from the fuel. CO and HC emissions were significantly diminished with TiO_2 blends compared to plain B20 and diesel, due to more complete combustion. NOx emissions increased with B20 but were slightly mitigated with TiO_2 additives, likely due to improved combustion timing and reduced peak temperatures. Smoke opacity was markedly lower in nanoparticle blends, especially at higher loads, with B20 + 50 ppm TiO_2 showing the lowest smoke levels. Among the tested concentrations, 50 ppm TiO_2 emerged as the optimal dosage, balancing improved performance and reduced emissions without causing injector clogging or adverse effects. The use of a CRDI engine further enhanced the benefits of TiO_2 addition by enabling precise fuel injection control, thereby complementing the combustion-improving properties of the nanoparticles.

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