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Enhanced Performance and Emission Characteristics of Soybean Biodiesel using TiO_2 Nanoparticles in CRDI Engines: A Comprehensive Analysis

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Abstract: Renewable and clean energy sources must replace conventional ones due to the dangerous effects of fossil fuel pollution. The impact of incorporating hydrogen and TiO_2 nanoparticles into Soybean biodiesel and its CRDI engine performance was assessed in this study. For engine operations, a 10 L/min hydrogen flow and 75 ppm of the nanoparticle also used. Experiments comparing diesel engines running on clean diesel to those with a B15 biodiesel mix (75% diesel and 15% biodiesel) found that the latter had better performance, and combustion behaviour with the inclusion of both hydrogen gas and cenoxite oxide. Brake fuel consumption was 16.12% lower and brake thermal efficiency was 3.53% better than diesel at 80% loading condition. By incorporating nanoparticles and hydrogen into the biodiesel mixture, we were able to reduce CO emission by 30%, HC by 50%, and smoke by 42%. On the other hand, comparisons to diesel showed an 12.15% rise in NOx. A mix of hydrogen and TiO_2 nanoparticles produced biodiesel with 9% greater in-cylinder pressure and 7% higher HRR. More power and efficiency from the engine are the outcomes of this blend's low ignition delay period under full load conditions. This experimental work has paved the path for diesel engines to run on biodiesel that is hydrogen-enriched and combined with nanoparticles.

Keywords: TiO_2, Emission characteristics, Soybean biodiesel, CRDI engine, Performance characteristics

1. Introduction

In the energy industry around the globe, the usage of fossil fuels is in rise. Fuels derived from fossil fuels are the backbone of the transportation and power generation industries. In terms of reliability and efficiency, petroleum has emerged as the go-to fuel for transportation and power generation [1]. The employment of efficient systems and increased economic growth are two positive outcomes, but there are also some unfavourable aspects. Due to population growth, industrialization, and increased urbanization, demand for petroleum fuels is on the rise, and some worry that it may run out soon [2]. The release of toxic gasses by vehicles powered by petroleum has also emerged as an environmental concern. The main cause behind the greenhouse gas effect, climate change and ozone layer depletion are emission from IC engines. Finding an alternative fuel that is both environmentally friendly and financially feasible while also reducing energy usage is, therefore, an urgent matter of paramount importance [3]. Diesel can be replaced with biodiesel, one of the alternative fuels that meets all the aforementioned requirements. It is possible to produce biodiesel straight from many oils, including those that are edible or not, used cooking oil, and tallow or lard, which are animal fats [4].

Because it is renewable and engine emission are lower with biodiesel, it is a cleaner and greener energy option than fossil fuels, which are becoming increasingly scarce. Researchers love biodiesel because it's easy to store, doesn't harm the environment, recyclable, requires minimal engine modification, and is always available [5]. Blending biodiesel with regular diesel allows for improved engine performance without engine modifications. As impressive as CI engines are in terms of performance metrics like BTE, ICP, BSFC, HRR and they also produce dangerous emission like CO, NOx, UHC, smoke opacity, CO2, soot, and CO [6, 7]. To effectively reduce emission of particulate matter (PM) from an engine's exhaust, a diesel particulate filter (DPF) can be installed. Filter structures, improved soot prediction, a novel catalyst composition, and other regeneration technologies linked to DPF have also been developed, all of which contribute to a decrease in PM emission [8]. These pollutants can have less of an impact on the environment if fuel is burned completely. One solution to get a high combustion rate is to reformulate the fuel [9],

[10]. The use of nanoparticles is one example of such a method. Nanoparticles added to fuel enhance combustion properties, decrease exhaust emission, and boost engine performance [11]. The fuel's density, viscosity, sulfur content, and volatility are all enhanced as a result. Nano-additives derived from metals modify properties like viscosity, pour and flash point.

Nano-additives containing oxygen enhance combustion because of the oxygen content. Nitrogen stability, flash point and calorific value were enhanced by nano additions due to their antioxidant properties. Nano additives that increase cetane delay and ignition temperature are used in engines [12, 13]. This study utilizes TiO_2 nanoparticles because to their potent antioxidant properties. Due to its rapid shift from Ce4+ to Ce3+ oxidation states, this nanoparticle has exceptional catalytic activity [14]. Nanoparticles improve fuel-oxidizer interaction due to ratio of surface-to-volume. In addition to improving combustion, the use of TiO_2 nanoparticles greatly decreased emission of CO and HC. The literature suggests that diesel engines run on a single biodiesel blended fuel have somewhat lower efficiency and more pollutants [15].

Using a one-cylinder four-stroke engine fuelled by combining diesel and algal oil, researchers investigated the effects of Titanium Dioxide. They discovered the kinematic viscosity and calorific value of fuel were both enhanced by nanoparticles addition to the fuel blend. When comparing B15 gasoline to TiO_2 mixed fuel, the BSFC was lower and BTE was better. In a one-cylinder CI engine, authors studied the performance of biodiesel blends containing carbon nanotubes (CNTs) combined with B5 and B10 Soybean oil [16]. Doped with 10% iron and 15% iron, respectively, TiO_2 nanoparticles were utilized. They found no notable changes in UBHC output and a 15.7% drop in NOx emission. When comparing emission and cylinder pressure, the 15% TiO_2 with B30 was better than the 10% TiO_2 with B30. So, they tested various blends and discovered that the one with 15% TiO_2 performed better in the engine. The authors tested a diesel-jatropha biodiesel blend fuel containing graphene nanoplatelets (GNP). The fuel was tested with varying doses of GNP, including 25, 50, 75, and 100 mg/L [17, 18].

When graphene nanoplatelets were added to the solution at 25–50 mg/L, the BTE rised by 25% and the BSFC fell by 20%. Using the same dosage of GNP also lowered engine emission of 65%UHC, 65% CO, and 55% NOx. Based on their research, the optimal concentration of GNP to boost engine performance is 50 mg/L. Another new trend is the use of hybrid nanoparticles in fuel mixes. The authors used a diesel water emulsion containing hybrid nanoparticles to study the engine's properties. Researchers used Span 80 and Tween 80 surfactant to mix nanoparticles of TiO_2 and Al_2O_3, with diesel water emulsion at concentrations of different ppm to create the test fuel. Based on the studies, BTE raised by 9%, BSFC decreased by 15%, and 11%, 28%. The authors combined tire pyrolysis oil with hybrid SiO2 and TiO_2 nanoparticles [19, 20]. With 70 mg/L of hybrid nanoparticles, they discovered 0.03 kg/kWh BSFC reduction and 2% enhancement in BTE. When compared to fuels that were blended separately, hybrid nanoparticles had lower ICP and HRR values. Hydrogen is a renewable, clean, and sustainable energy source that is drawing attention from academics in the field of renewable energy. It may be used in a variety of contexts and has a long history of use. Hydrogen (H2) is quickly becoming the energy source of choice in many different industries. A lot of car companies are now working on cars that run on hydrogen. Hydrogen gas was utilized as source in fuel cells, which then undergo electrochemical reactions to produce clean energy. It will take a number of years and a lot of money to finish developing this technology [21]. Burning hydrogen with oxygen produces no hazardous emission; it is colourless and odourless. Natural gas, renewable energy, nuclear power, and biomass can all be used to create it. Due to unique physical and chemical properties, hydrogen is well suited for widespread usage as an energy carrier in IC engines.

While hydrogen reduced combustion duration (CD), it enhanced a number of combustion characteristics like ignition delay, current ratio and internal combustion pressure. The combination that included 10 L/min of H2 performed better when tested at full load. The nitrides and oxides emission are the primary concern when employing biodiesel blends in Internal Combustion engines [22]. The local ecosystem suffers when this pollution is released into the air. Using a combination of fuel injection tactics is one of the NOx-controlling methods proposed by researchers. To study combustion and emission parameters, they changed the pre-injection fuel mass ratio (PMR) and pre-injection timing (PT). Under ideal circumstances of PT 40 and PMR 0.4, NOx emission were lowered by 46.43%-87.18% and HC emission by 24.05%-38.03%, respectively. It is clear from the relevant literature that several studies have investigated the use of H2 as an additional fuel for CI engines. Results were better when hydrogen was added to diesel engine applications compared to operations using only gasoline. There is a clear correlation between the inclusion of nanoparticles in the fuel mixture and enhanced fuel quality, engine performance, combustion efficiency, and emission characteristics. It becomes essential to use H2 with formulated fuel in CI engine applications when utilizing it alone. Nevertheless, there is a dearth of literature on studying engine performance with nanoparticles added to biodiesel blends and H2 enrichment [23, 24].

This study aims to find a replacement for diesel that is as efficient as current energy sources. Consequently, it is centred around enhancing engine performance with the use of TiO_2 nanoparticles that have been hydrogenated and are powered by SBO biodiesel and diesel mixtures. Despite the known environmental impact of fossil fuels, the performance enhancement potential of hydrogen-enriched and TiO_2 nanoparticle-infused biodiesel blends remains underexplored. Current literature lacks comprehensive experimental analysis on the combined effects of these nanoparticles and hydrogen on engine performance and emission in CRDI engines. Therefore, this research specifically targets gaps in understanding the combustion behavior, emission reduction, and engine performance improvement facilitated by these additives.

2. Materials and Methodology

2.1 Extraction of Biodiesel from Soybean Oil

Producing biodiesel through the transesterification process led to a less viscous end product. The oil's triglycerides were converted to methyl esters by chemical reaction in this process shown in table 1. The presence of catalysts causes the triglycerides to react with alcohol; catalysts might be acidic, basic, or enzymatic in nature, among other instances. Soybean oil (SBO) was sourced from a local market in the Chennai, Tamil Nadu, India area for this research. By using filter paper, the oil was filtered to remove suspended particles before being warmed at 60°C for 30 minutes to eliminate moisture. A homogeneous catalyst is created ready by merging potassium hydroxide (KOH) and methanol and used to carry out the transesterification reaction. A hot plate and reflux condenser were employed to conduct the reaction, which lasted two hours at 60°C and a methanol-to-oil ratio of 6:1. The concentration of the catalyst was kept at 1%. The glycerol and biodiesel separated into their own layers the following day after the reaction was finished, so they were moved to separate funnels and left overnight. Using the funnel, we were able to separate the glycerol by-product, and then we rinsed the biodiesel with hot water to get rid of remaining glycerol. When cycles continued, the water gradually turned clear. After the biodiesel had been dried with a hot air blower until it was completely transparent, it was sealed in glass container and kept for later usage.

2.2 Analysis of XRD

The TiO_2 nanoparticles are studied employing X-ray diffraction method shown in figure 1. The XRD equipped with Cu K radiation is used to conduct the test. The 2θ angles at which these peaks were seen were 31.4°, 38.7°, 51.7°, 61.3°, and 66.5°, with corresponding d-values of 2.946Å, 2.551Å, 1.807 Å, 1.539 Å, and 1.475 Å. The nanoparticle's crystalline structure is confirmed by the prominent peaks seen in the pattern. The XRD pattern does not show any additional peaks, which confirms the nanoparticle's purity.

Due to higher energy surface area, Titanium Dioxide (TiO_2) is the nanoparticle added in this experiment. All of the samples used in the experiment have the same nanoparticle dose of 75 ppm. Table 2 shows the detailed parameters of the nanomaterial that was stated earlier.

2.3 Test fuel preparation

The hydrogen for the biofuel blends containing nanoparticles comes from a 170-bar pressure tank. A 10 L/min of hydrogen fixed flow rate was kept by means of hydrogen regulator. The dosage of TiO_2 nanoparticles and the flow rate of hydrogen are used is shown in Figure 2. For the engine testing, we used the following fuel blends: SBOB15 (15% SBO biodiesel+ 75% diesel), SBOB15 + 10H2, SBOB15 + 75TiO_2 (SBOB15 blend+75 ppm TiO_2), SBOB15 + 75TiO_2 +10H2, D100, and D100+H2 (10 L/min H2). Mixtures of biodiesel with nanoparticles are prepared using a probe sonicator and a conventional magnetic stirrer. To prevent nanoparticle aggregation in the fuel mixture, sonication is applied for 30 minutes.

Table 1. Properties of SBO biodiesel and SBO

Properties	Diesel	SBOB15	SBOB15 + 75TiO_2
Density (kg/m^3)	820	824	816
Kinematic viscosity at 40ºC (mm^2/s)	3.68	4.85	5.32
Cetane number	52	61	52.4
Cloud point (ºC)	5.9	-1	-4
Calorific value (kJ/kg)	46,526	42.584	41,586
Pour point(ºC)	4	-4	-4
Flash point(ºC)	59	168	169.6

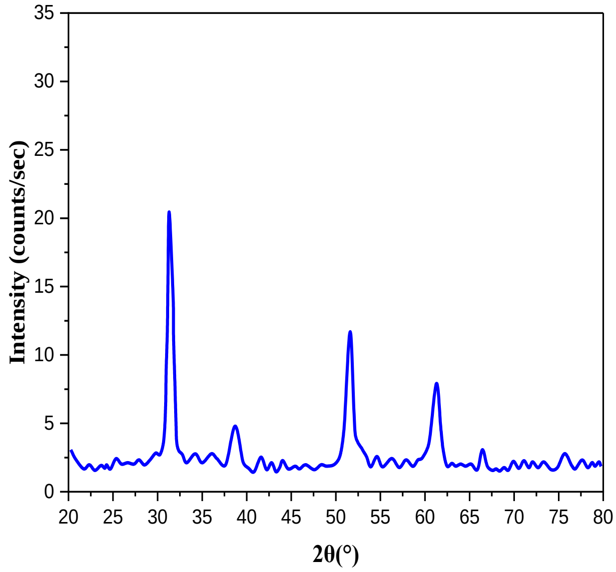


Figure. 1 X-Ray Diffraction of $nTiO_2$ particle

Table 2. Properties of TiO_2 nanoparticle

Parameters	Specification
Refractive Index	2.5–2.9 (Anatase), 2.7 (Rutile)
Particle size	Typically, 1–100 nm (Nanoparticle range)
Thermal Conductivity	11.7 W/m·K
Molecular weight	78.426 g/mol
Melting Point	1,843°C
Color	White
Surface Area	50–200 m²/g
Density	4.23 g/cm³
Boiling point	2,972 °C

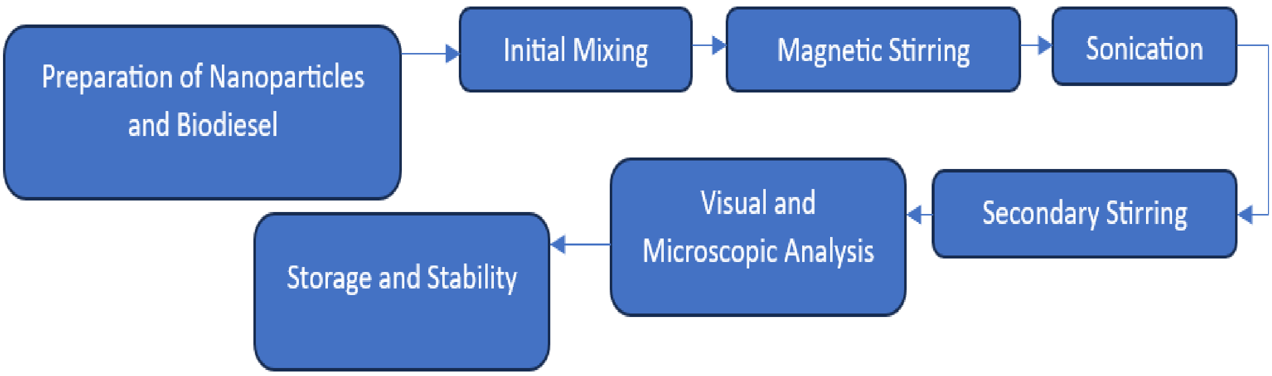


Figure 2. Step-by-Step of TiO_2 nanoparticles process in biodiesel

3. Experimental Setup and Procedure

A four stroke, single-cylinder, water-cooled, CI engine running at 1600 rpm was utilized in the present investigation shown in figure 3. The power that the engine produces can be measured using an electrical dynamometer. A crankshaft is utilized by crank angle encoders to measure the crank angle. The chamber head is equipped with a piezoelectric pressing factor transducer that is utilized for the purpose of estimating the pressure within the cylinder. The dregs statement and unpleasant responses from the fuel line are finally put to rest with the installation of new gas tank and fuel line. Regular fuel channel cleaning is essential for maintaining the engine's top testing condition. A computer was connected to the pressure signals through a high-speed data collection system so that the combustion parameters could be recorded.

The CI engine's specifications are shown in Table 3. An AVL DIGAS 444 gas analyzer was used to record emission parameters such as CO, HC, and Nox shown in table 4.

The engine receives hydrogen fuel at a high pressure of about 2 bar due to the pressure regulator. The flow rate is maintained at 10 L/min with the help of a control valve and a flow meter. The hydrogen flow line has a flame arrester attached to it to avoid any potential backfire. The motor oil was examined at the end of every hydrogen enrichment study. The engine is initially ignited with diesel and operated under no load. When everything was stabilized, we recorded the readings under each load scenario and used them as a benchmark. Then, it was run with hydrogen enrichment rate of 10 L/min while readings were recorded. For the biodiesel blends that were made, the identical process was used for SBOB15, SBOB15 + 10H2, SBOB15 + 75TiO_2, and SBOB15 + 75TiO_2 + 10H2. At 23 minutes prior to top dead center, injection timing is selected and pressure is kept at 600 bar. Instrument accuracy, ambient circumstances, human perception, and other variables all contribute to measurement errors, which are unavoidable in analysis. The study's validity and reliability are shown by the degree of uncertainty. Unlike random errors, which can lead to values in rate uncertainty, fixed faults happen during the direct estimation and are immediately observable. Equation (1) is used to compute the overall uncertainty, which comes out to be ± 2.16%. The percentage of uncertainty for each parameter is shown in Table 5.

Every measurement inherently carries some degree of error or uncertainty, regardless of the tool used. Due to the random nature of certain errors, it becomes essential to have a consistent mathematical approach to express this uncertainty. This is why theoretical methods are employed to evaluate the extent of uncertainty across different measurements.

Table 3. Details of the engine

Factors	Details
No of cylinders	Single cylinder
Rated power	3.5 kW
Swept volume	661.45 cc
Fuel injection type	Direct injection
Span of Connecting rod	234mm
No of stroke	Four
Compression ratio	18.00
Bore and Stroke length	87.5 and110 mm
Dynamometer	Eddy current

Table 4. Details of the Exhaust Gas Analyser

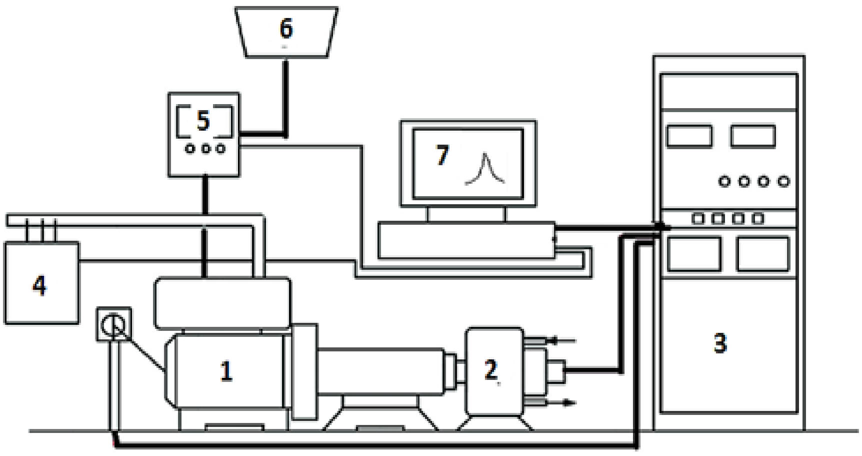
Apparatus	Gas	Range	Tolerance
AVL 437	Smoke (BSN)	0-100	+1%
AVL 444	HC (ppm)	0-20000	+10
	NOx (ppm)	0-5000	+10
	CO	0-10%	0.01

Table 5. Proportion of parameter uncertainty

Parameters	Uncertainty (%)	Accuracy
Brake Thermal Efficiency	±1.049	-
Brake Specific Fuel Consumption	±0.329	-
Carbon Monoxide	±0.364	±0.01 ppm
Exhaust Gas Temperature	±0.23	±1C
Nitrogen Oxides	±0.872	±10 ppm
Smoke Opacity	±1.24	±1%
Hydrocarbons	±1.0	±10 ppm

4. Results and Discussions

Using D100 as reference [12], we measured the impacts of TiO2 and H2 on its performance, emission, and combustion parameters. We evaluate diesel to each of the prepared fuel mixtures using a battery of performance indicators, including BTE, BSFC, and EGT. Hydrocarbons, nitrogen oxides, smoke, and carbon monoxide are the main components studied in engine exhaust.



1. Diesel engine 2. Dynamometer 3. Engine control panel 4. Exhaust gas analyzer 5.Fuel gauge 6. Fuel tank 7. Computer

Figure 3. Test Engine Setup

4.1 Performance Behaviour

4.1.1 Brake-specific fuel consumption (BSFC)

It is a metric for evaluating the efficiency with which an engine utilizes gasoline in relation to the properties of the fuel. Scientists have discovered that engines that run on biodiesel have a higher BSFC. Figure 4 demonstrates that under 80% loading conditions, the fuel consumption of the SBOB15 blend is 16.12% higher than that of the D100 blend. That biodiesel isn't very calorically dense could be one reason. It basically means that more fuel injection is needed to keep same output power. The inclusion of hydrogen and nanoparticles tends to decrease as load increases because higher loads lead to improved combustion stability, reducing the reliance on additional hydrogen and nanoparticles for performance enhancements.

To enhance fuel economy in the engine by 14.23% compared to SBOB15, 75 ppm of TiO_2 is added to biodiesel blend. Nonetheless, it surpasses clean diesel by 1.99%. The biodiesel blend's BSFC drops when hydrogen is introduced, in comparison to SBOB15. The BSFC of the SBOB15 + 10H2 blend is 8.72% lower than that of SBOB15 alone, but it is 6.62% higher than pure diesel. Adding TiO_2 and H2 to biodiesel mixture, however, decreases the BSFC by 28.04% when compared to plain biodiesel blend, and it also exhibits the same performance as diesel. The increased temperature inside the cylinder caused by H2 higher calorific value speeds up the combustion process, leading to a reduced BSFC and an increased mean indicated pressure. The lowest BSFC is seen at 80% load state for all fuel blends. Under load, brake-specific fuel consumption rises because more fuel has to be pumped into the cylinder at higher engine speeds.

4.1.2 Brake thermal efficiency (BTE)

Figure 5 displays the range of BTE values for all tested oils, including SBOB15, SBOB15 + 10H2, SBOB15 + 75TiO_2, and SBOB15 + 75TiO_2 +10H2, D100, D100+H2 under varying loading conditions. A greater BTE indicates better performance, as the BTE typically rises with the load. Under all load conditions, the SBOB15 mix demonstrates lower BTE compared to straight diesel. Because biodiesel is denser and stickier than regular diesel, it has longer ignition delay and a worse atomization. But engine performance suffers when biodiesels have a low cetane number.

Fuel mixtures could be made more thermally efficient with inclusion of TiO_2 nanoparticles, leading to reduced fuel usage overall. With respect to BTE, the SBOB15 + 75TiO_2 blend outperforms a neat biodiesel blend by 16.08%. Increased catalytic activity, high thermal stability, and the oxygen-storing capacity of TiO_2 all contributed to better BTE by making fuel burn more efficiently. Nanoparticles, with their increased evaporation rates, also improve air fuel mixing, which in turn aids in more complete combustion. While the BTE of SBOB15 + 10H2 is 11.37% higher than that of SBOB15 alone, it is still 5.07% lower than D100 at full load after adding 10 L/min H2 to the biodiesel blend. Injecting hydrogen into engine's air intake manifold increases its BTE. At optimal load, D100 + 10H2 demonstrates BTE of 29.47%. Injecting hydrogen into engine's air intake manifold increases its BTE. In a fully powered state, the BTE of D100 + 10H2 is 29.47%. The main cause of this is the increased flammability and fast flame velocity of hydrogen fuel. The improved mixing of the hydrogen, which speeds the flame movement within the cylinder, also leads to improved thermal efficiency. The study found that adding TiO_2 nanoparticles to hydrogen improved the engine's performance. In comparison to D100 under 80% loading conditions, the blend SBOB15 + 75TiO_2 +10H2 exhibits a 3.88% increase in BTE.

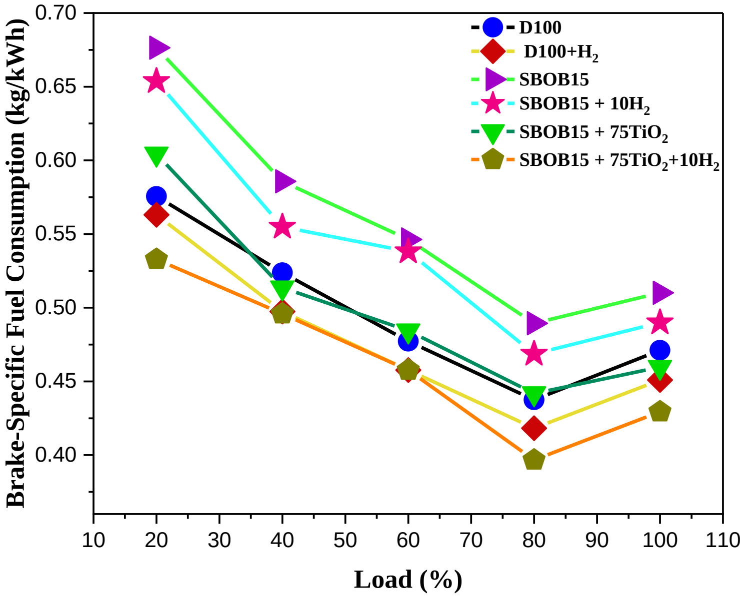


Figure 4. Difference of load vs BSFC

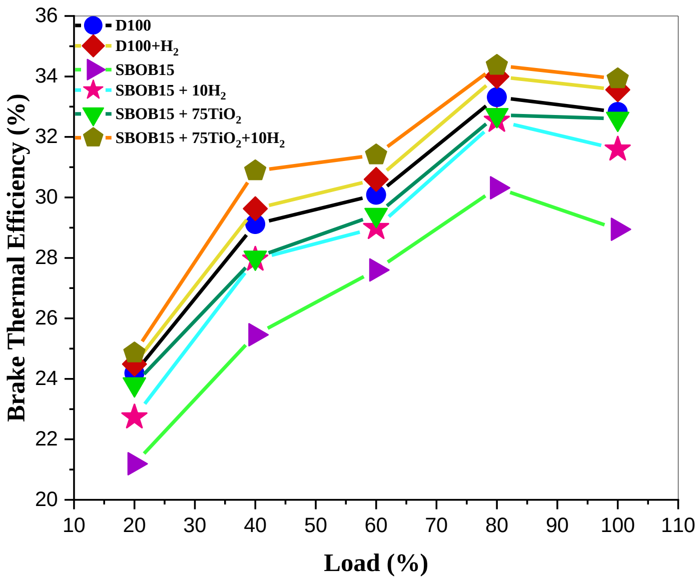


Figure 5. Difference of load vs BTE

The rise in BTE is due in part to hydrogen diffusivity and in part to the accelerated evaporation of TiO_2 nanoparticles. Nanoparticles' catalytic effect and an increase in oxidation rate can shed light on power developments [25, 26]. But as the nanoparticles weaken under maximum load, BTE drops.

4.1.3 Exhaust gas temperature (EGT)

Using exhaust gases and its emitted heat, one may determine the exhaust gas temperature. EGT, a measure of combustion quality, increases monotonically with increasing load for all fuel samples. This is because the increased fuel consumption to meet the load demand results in higher internal cylinder temperatures [27, 28]. The variation in EGT under various loads is seen in figure 6. The EGT grows in proportion to the magnitude of the applied load. The EGT of the biodiesel mixture is higher than that of diesel. Adding hydrogen to regular diesel fuel raises EGT readings regardless of load regime.

Figure 6 shows that the tendency of including hydrogen to biodiesel blends is similar to diesel's trajectory.

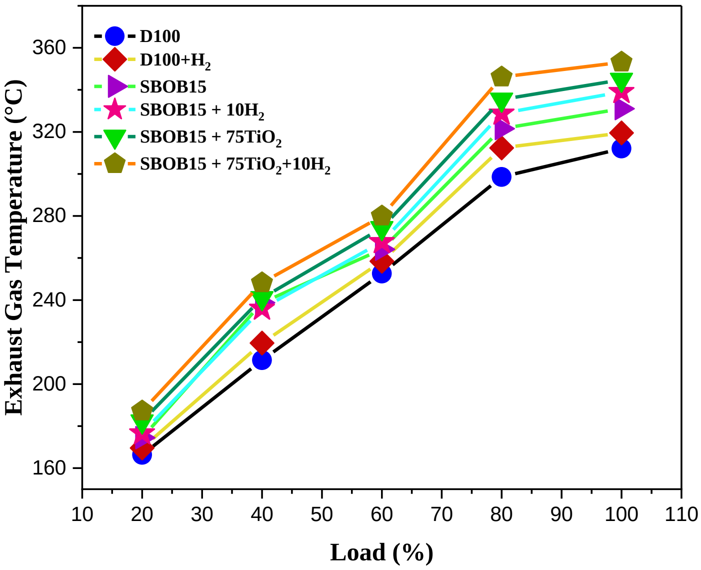


Figure 6. Difference of load vs EGT

The EGT of the SBOB15 + 10H2 mixture is 11.36% higher than that of D100. An increase in the self-ignition value of hydrogen and more energy produced during combustion are results of an improvement in EGT, which allows fuel to be burned more rapidly [29, 30]. Figure 6 shows that EGT rose by 7.02 % compared to SBOB15 and 14.53 % compared to D100, in addition to TiO_2 nanoparticles. Blended fuel using TiO_2 nanoparticles used more oxygen, which boosted combustion, raised temperature, and improved EGT. At 80% load, the blend with the highest EGT is SBOB15 + $75TiO_2$ + 10H2. By combining the effects of hydrogen and nanoparticles, the adding of TiO_2 and Hydrogen to the bio-diesel mixture increased the EGT values by 16.03% as compared to D100, the higher flame speed of hydrogen and improved oxygenation by TiO_2 nanoparticles lead to more efficient and complete combustion, increasing the EGT values.

4.2 Emission characteristics

4.2.1 CO emission

Emission of carbon monoxide occur when the power generated by an engine is not completely converted into mechanical energy. An important metric is the fuel-to-air equivalency ratio. The CO emission range for all fuel blends evaluated under various load conditions is displayed in Figure 7.

Too much fuel inside the cylinder to kept a constant speed led to incomplete combustion, which in turn increases CO emission under high-load conditions. When compared to D100, SBOB15 blend reduces by 25% when loaded to 80%. Biodiesel produces less carbon monoxide during combustion than regular diesel due to its oxygen-rich makeup. Incorporating 10 L/min of H2 more, decreases 10%CO emission compared to SBOB15. Hydrogen enrichment enhances air/fuel mixing and raises the hydrogen-to-carbon ratio, both of which lead to a decreased need for carbon-based fuel. The combustion process is accelerated and the mixture is made more uniform with the help of hydrogen due to its high diffusivity. Adding TiO_2 nanoparticles reduced CO emission by an additional 15% compared to SBOB15 running at maximum load. Enhancing thermal and combusting efficacy can be achieved by the use of nanoparticles that possess a greater surface/volume ratio along with robust catalytic activity. A complete combustion process is accomplished with reduced CO emission by combining hydrogen's carbon-free structure with TiO_2 's high energy surface area, because hydrogen's carbon-free structure eliminates CO production by promoting complete combustion, while TiO_2 nanoparticles act as catalysts, enhancing oxygen availability and facilitating efficient fuel oxidation, reducing CO emission.

4.2.2 HC emission

Figure 8 shows that when the load condition goes from 40% to 100%, the HC emission goes up. There are a lot of factors that contribute to poor mixture production, such as insufficient atomization, unequal or excessive penetration, inadequate injection pressure, and sac volume/hole leakage. In contrast to D100 and D100+H2, SBOB15's HC emission rate is % lower, as seen in the results. After adding TiO2 to the biodiesel mixture, it was found that the HC 29.32 emission were reduced. Due to its oxidation catalytic role, TiO2 reduces the activation temperature of carbon combustion, boosts HC oxidation, and improves complete combustion. At full load, adding 10 l/min of hydrogen gas reduces HC emission by 33.48% compared to diesel. Hydrogen fuel contributes to reduced HC emission due to its lack of carbon atoms.

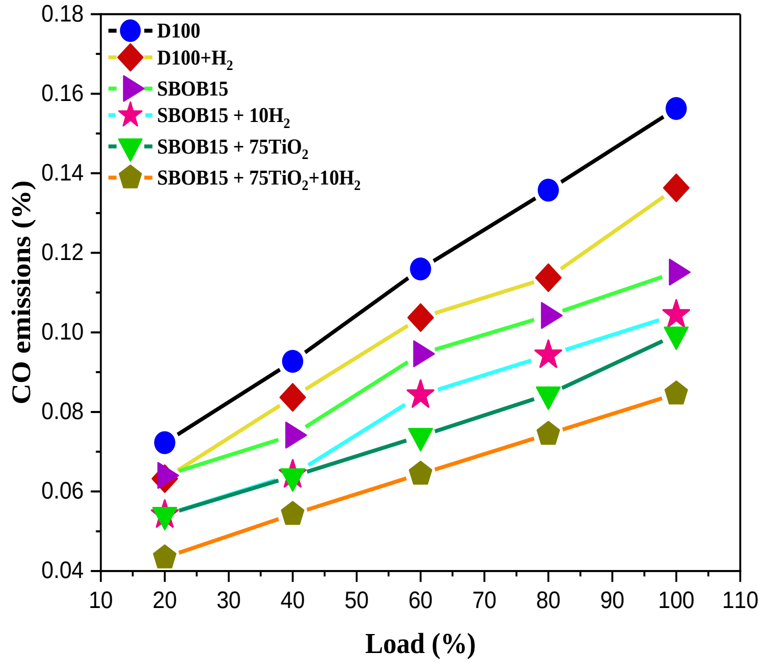


Figure 7. Differences of load vs CO

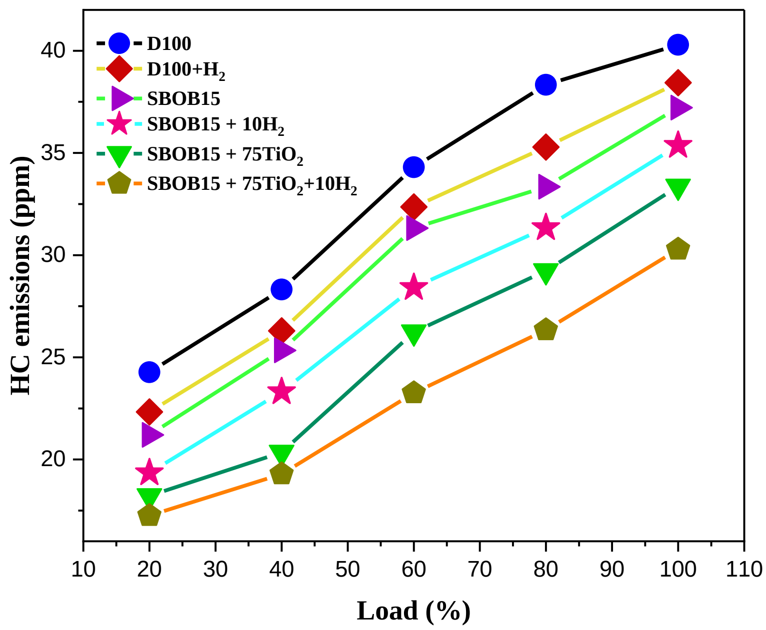


Figure 8. Differences of load vs HC

The fuel blend with the fewest HC emission is the one shown in Figure. 8, which is SBOB15 + 75TiO_2 +10H2. It reduces HC emission from D100 by 50% and from the SBOB15 mix by 30% at full load. Hydrogen-enriched biodiesel contains nanoparticles with a high surface-to-volume ratio, it burns fuel completely and produces very little HC emission.

4.2.3 NOx emission

Diesel engines release nitrogen oxides (NOx) into the air as a byproduct of their combustion process. Both human and environmental health are severely impacted. Efforts to lessen its impact are, hence, paramount. The impact of incorporating TiO_2 nanoparticles and hydrogen under different load scenarios. Figure 9 shows that the NOx emission rises in relation to the load. At 80% loading, the NOx emission from SBOB15 biodiesel blends are 4.19 % greater than those from diesel. Because of its comparatively high oxygen concentration, biodiesel facilitates full combustion, leading to increased cylinder temperature and emission.

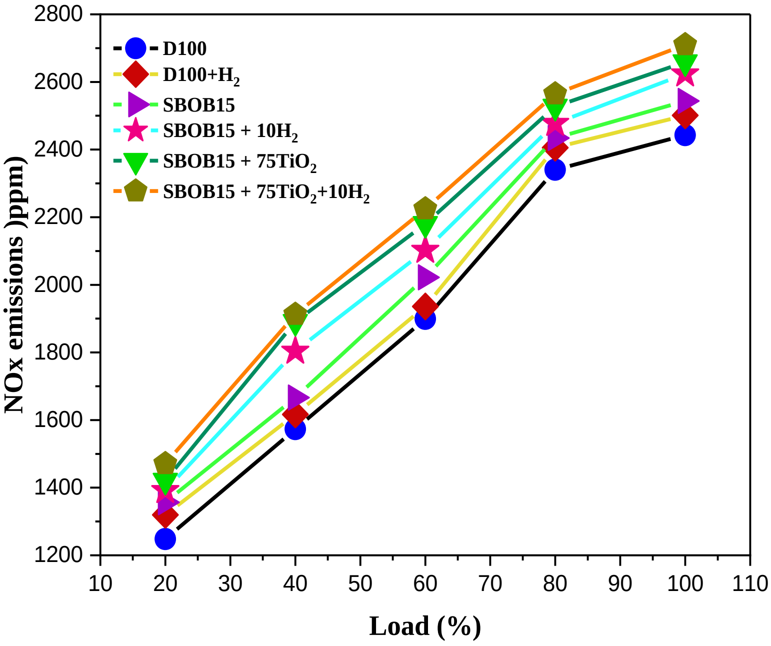


Figure 9. Differences of load vs Nox

The blend with TiO_2 nanoparticles increases NOx emission by 9.23% as equated to D100. The sole cause of NOx production when using a higher TiO2 concentration is the additional oxygen introduced to the fuel by the nanoparticles. Increased in-cylinder temperature and NOx emission result from fuel evaporation, which is facilitated by nanoparticles improved thermal conductivity. The enrichment of hydrogen causes an increase in emission of nitrogen oxide. There is a 2.63% increase in NOx emission from the D100+H2 blend compared to diesel, and a 7.55% increase from the SBOB15 + 10H2 blend. Because H2 has a higher calorific value than air, it could cause NOx emission if the cylinder temperature increases. The combination of nanoparticles and hydrogen produces the highest NOx emission at 20% - 100% load conditions. This blend outperforms diesel in terms of nitrogen oxides (NOx) production by 12.15% when loaded to capacity. Maximum NOx emission are produced by an interaction between improved nanoparticle air-fuel mixing and enhanced combustion properties of hydrogen.

4.2.4 Smoke emission

Figure 10 displays the smoke emission' fluctuation across all fuel blends under varying loading situations. In environments deficient in oxygen atoms, it usually forms in areas rich with fuel. The results show that the smoke emission are getting worse as the load percentage gets higher. Because not all of the fuel that is injected is burnt, smoke emission rise as loads is increased to meet demand. Comparing SBOB15 and D100 biodiesel blends, the former produces 10% less smoke. The reason behind this is that biodiesel burns more completely in the cylinder due to its increased oxygen content in its molecular composition. But biodiesel's viscosity influences smoke formation due to poor atomization. At full load, adding 10 liters per minute of hydrogen gas reduces smoke emission by 18%. H_2 induction makes fuel more homogeneous, which improves combustion, and the gas's high heating value oxidizes soot particles at high temperatures. When compared to SBOB15, the biodiesel mixes with TiO_2 added reduces smoke by an additional 22.36%.

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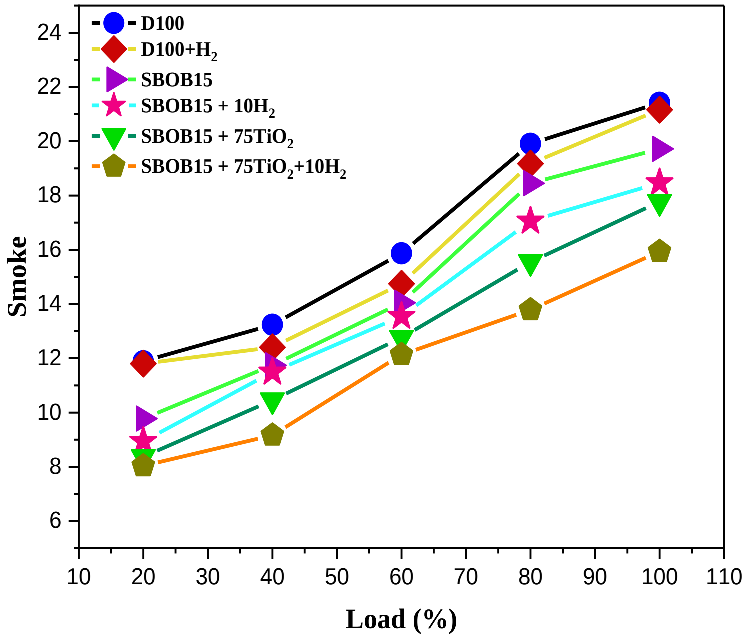

Figure 10. Differences of load vs smoke

Nanoparticles' oxygen concentration increased combustion properties, which in turn reduced smoke opacity. This is mostly due to nanoparticles' high surface area to volume ratio, which increases evaporation in the combustion chamber and improves fuel-air mixing. Adding nanoparticles and hydrogen, both of which have better combustion characteristics has the cumulative effect of lowering smoke generation. More gasoline is fed into the engine cylinder at full load, which results in a 15% increase in smoke emission for the SBOB15 + 75TiO_2 + 10H_2 blend.

4.3 Combustion characteristics

4.3.1 In-cylinder pressure

As fuel is burned within the engine cylinder, a pressure known as the in-cylinder pressure is created. All of the fuel mixtures tested showed fluctuations in cylinder pressure at different crank angles. There is a 21% difference between diesel and SBOB15 at peak pressure, which is 65.95 bar. The poor evaporation qualities and low calorific value of the biodiesel blend cause the cylinder pressure to rapidly fall. Weak evaporation properties cause inefficient mixing of fuel and air, which turn causes the inefficient combustion. The in-cylinder pressure of the nanoparticle-added biodiesel blend SBOB15 + 75TiO_2 is 25% greater than that of neat biodiesel blends, as demonstrated in Figure 11. This indicates that the combustion is better and the heat release is faster. Their ability to produce hydrogen gas at elevated temperatures improves combustion. The TiO_2 nanoparticle's oxygen content also helps burn the fuel to its final product, which shortens the ignition delay. Increased ICP and better combustion characteristics are both caused by this shorter ignition delay.

The results demonstrated that compared to D100 and SBOB15 blends, biodiesel blends with hydrogen added achieve in-cylinder pressures that are 2.5% and 23.75% higher, respectively. Pressure increased under higher loading circumstances when H_2 was added. Internal pressure increases due to fast charge oxidation brought on the high hydrogen flame speed. A low load makes it impossible to ignite and maintain a high enough flame speed for the hydrogen-air mixture. By the way, when compared to SBOB15 and neat diesel, the in-cylinder pressure while using D100 + 10H_2 was 24.4% higher, according to the data. The smaller quenching gap and higher calorific value of hydrogen relative to plain diesel are responsible for this phenomenon. With 93.75 bar cylinder pressure at crank angle of 356^o, an 8% increase above D100, the fuel mixture SBOB15 + 75TiO_2 +10H_2, which includes both nanoparticles and hydrogen gas, is demonstrated. The improved fuel evaporation capabilities of nanoparticles, in conjunction with the combustion qualities of hydrogen, aid in full combustion led to high ICP.

4.3.2 Net Heat Release Rate

Figure 12 displays the relationship between crank angle and the net heat release rate for all of the gasoline blends that were evaluated. The findings show that diesel fuel's higher calorific value causes it to generate more heat compared to SBOB15. On top of that, diesel with hydrogen added (D100 + 10H_2) enhances the quantity and rate of heat emission. There are actually two stages of combustion in engines that use dual fuels. Premixed combustion results in a rapid rise in heat release (HRR) is moderated and controlled at diffusion phase.

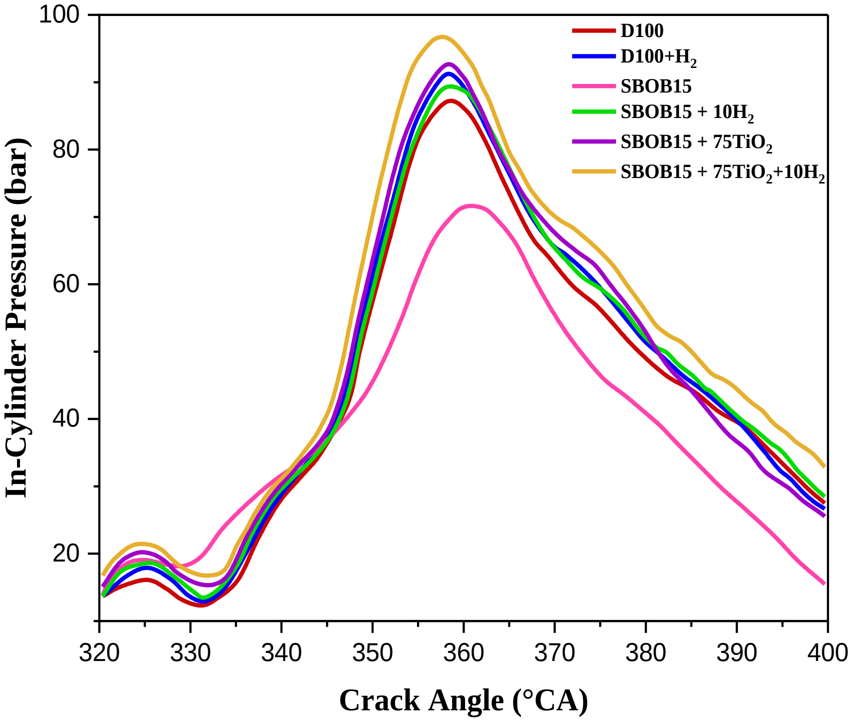

Figure 11. Difference of crank angle vs in-cylinder pressure at full load condition

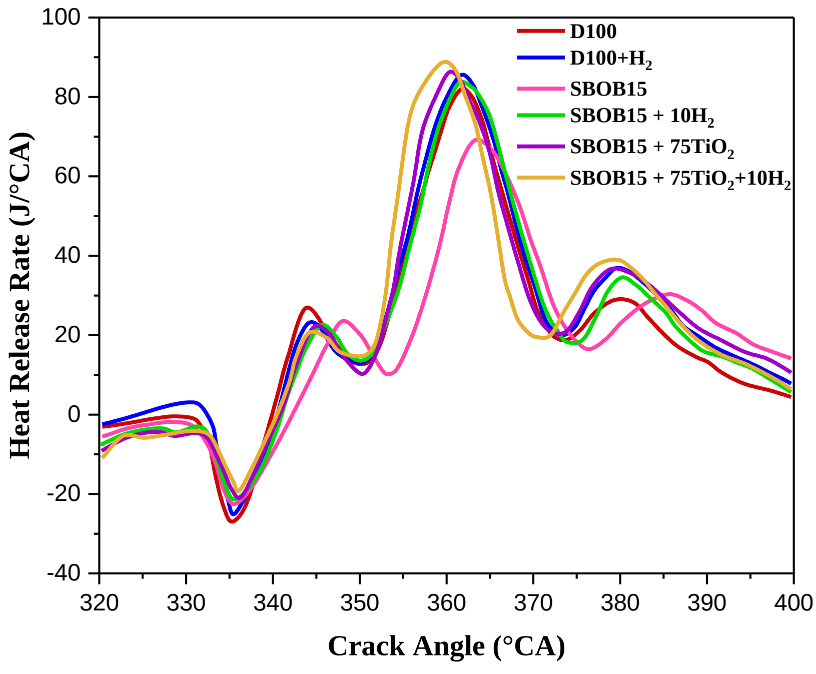

Figure 12. Difference of crank angle vs heat release rate at full load condition

As the result of lean mixture created by reduced fuel burning at part load, HRR decreases as H_2 enrichment increases. Due to hydrogen's high diffusivity, H_2 enrichment under high loads increases the maximal HRR. A negative HRR value was acquired prior to initiating the combustion, as can be shown in Figure 12. This occurs as a result of the engine soaking up ambient heat and the evaporation of fuel held during the ignition delay interval. The HRR number turns positive as soon as combustion starts. Figure 12 shows that at a crank angle of 361º, the HRR of the SBOB15 + $10H_2$ blend is 19.3% greater than that of SBOB15. Biodiesel has the high viscosity and low calorific value than diesel, the blend SBOB15 has 17% lower HRR than D100. The oil's increased viscosity causes the gasoline to enter the cylinder in a bigger particle size. During a part-load condition, the fuel droplets cannot be cracked because to the low internal cylinder temperature. These droplets initially have HRR, but they break down into smaller particles as the in-cylinder heat increases at maximum load, foremost to further even ignition and improved heat release rate. By accelerating the passage of heat from the fuel to the air around it, TiO_2 nanoparticles enhance fuel combustion. The result is a shortening of the physical and chemical reaction durations. The premixed combustion mixture stores more energy, which means that combustion starts sooner and produces more heat overall. Figure 12 demonstrates that the HRR of the SBOB15 + $75TiO_2$ blend is 20.2% greater than that of SBOB15 alone. The HRR is enhanced when nanoparticles and hydrogen are added to the biodiesel mixture simultaneously. The HRR of the SBOB15 + $75TiO_2$ +$10H_2$ blend is 21.5% more than that of SBOB15, and it is 6% higher than that of D100. The combination of TiO_2 's high heating value and hydrogen's quick combustion speeds up the fuel burning process, which in turn increases the heat release rate.

4.3.3 Ignition delay

The ignition delay for the fuel combinations tested decreased with increasing engine load, according to the data. Reduced pressure, lower temperatures of the remaining gas and cylinder walls, and an insufficiently performing engine all contribute to a extended explosion delay and a later start of combustion. So, the increase stroke is when the engine loses power and efficacy due to the highest fuel gas consumption. Raising the in-cylinder temperature and pressure via earlier fuel injection shortens the ignition delay period. A lengthier ignition delay period is associated with the SBOB15 biodiesel blend compared to pure diesel. At full load, the ID period is 10% more than diesel, and at 20%, it's 12.15% longer. This is because the biodiesel blend's high viscosity leads to extensive vaporization, which in turn creates a longer ID and significant heat absorption. Adding hydrogen to fuel mixes shortens the ID period. Under full load conditions, the ID period is 5.52% longer in the SBOB15 + $10H_2$ blend than in diesel, but it is 7% shorter in SBOB15 alone. Due to its higher flame speed and higher self-ignition temperature, hydrogen causes the cylinder wall to become hotter. This, in turn, reduces the ignition delay time and demonstrates that the fuel-air mixture burns thoroughly and rapidly. A longer ignition delay period is caused, in part, by the stronger chemical reaction exhibited by the greater cetane number of hydrogens in biodiesel blends. Decreased ignition delay is another effect of adding nanoparticles to gasoline mixtures.

At 100% loading condition, the blend SBOB15 + $75TiO_2$ displays a 17.05% drop in ID compared to SBOB15, as shown in Figure 13. The fuel is atomized well and evaporates quickly due to its high surface area to volume ratio, which improves combustion and decreases ignition delay. To ensure full fuel combustion, oxygenated additives such as metal oxide nanoparticles are used. With the addition of TiO_2 and H_2, the ignition delay of the SBOB15 + $75TiO_2$ +$10H_2$ biodiesel mix is reduced compared to SBOB15 under all load conditions. Its ID period is 12.15% shorter than diesel at 100% load. When compared to diesel under full load conditions, the ignition delay is reduced when hydrogen and nanoparticles are used together. With hydrogen's diffusive properties and metal-oxide nanoparticles' strong thermal conductivity, the heat transfer rate is increased, leading to the shortest ignition delay period.

5. Conclusion

This study analyses how a soybean oil-powered biodiesel blend affects CI engine performance via hydrogen enhancement and TiO_2 nanoparticle dosage. Engine performance is better with hydrogen gas and TiO_2 nanoparticle biodiesel blends. Experimental results can be used to draw these conclusions.

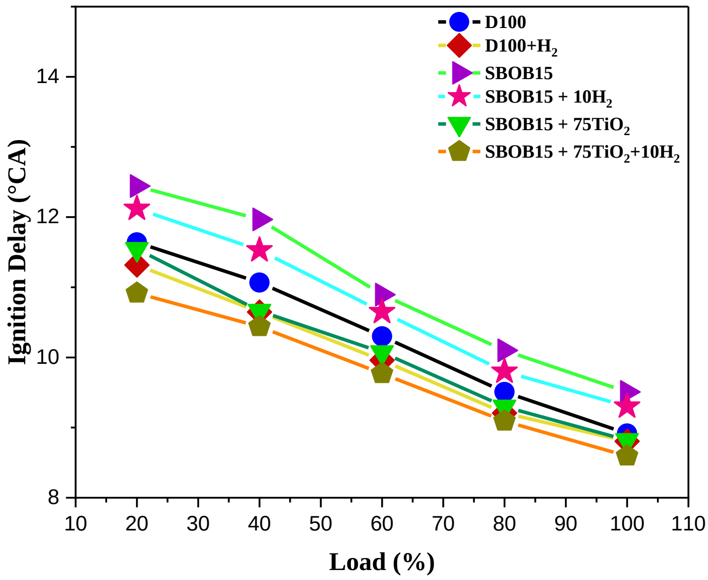

Figure 13. Difference of load vs ignition delay period

Enhanced performance using hydrogen and titanium dioxide nanoparticles. SBOB15 + 10% H2 increased diesel engine BTE by 11.37% and SBOB15 + 75% TiO_2 by 16.08% compared to bio-diesel. Hydrogen and nanoparticles synergistically produce biodiesel's greatest BTE, which boosts engine power. SBOB15 + 75TiO_2 +10H2 has 3.53% higher BTE than diesel. Blends of biodiesel and pure diesel have a greater BSFC. The engine uses less petrol with more hydrogen. H2 and TiO_2 fuel mixes lower diesel fuel utilisation by 16.12%. A mix is SBOB15 + 75TiO_2 +10H2. Nanoparticles, biodiesel, and hydrogen, which contain oxygen molecules and have high heating value, improve fuel efficiency in the cylinder. Each fuel blend has an EGT that increases with load. SBOB15 + 10H2, SBOB15 + 75TiO_2, and SBOB15 + 75TiO_2 +10H2 blends outperform regular diesel by 11.36%, 14.530%, and 16.03%, respectively. Hydrogen gas and nanoparticles enhance exhaust gas temperatures. However, EGR could reduce that.

Oxygenated fuel in CI engine applications reduces carbon monoxide emission. By adding H2 and TiO_2 to biodiesel, CO emission have increased. SBOB15 + 75TiO_2 +10H2 decreases CO emission by 30% at 100% load compared to pure biodiesel. Adding hydrogen gas and nanoparticles to biodiesel reduces HC and smoke emission. Since hydrogen fuel has no carbon atoms and TiO_2 includes oxygen, it can be entirely burnt with the lowest HC and smoke emission. Diesel emits 42% more smoke and 50% less HC than SBOB15 + 75TiO_2 - +10H2. Using biodiesel mixtures as primary fuel releases nitrogen oxides, damaging the environment. SBOB15 + 10H2 blend, SBOB15 + 75TiO_2, and SBOB15 + 75TiO_2 - +10H2 mix all increase 7.55%, 9.23%, and 12.15% above clean diesel. However, suitable measures can reduce this harmful emission. SBOB15 + 75TiO_2 mix has 5% higher in-cylinder pressure than D100, while SBOB15 + 10H2 blend has 2.63% higher. The fuel mixture SBOB15 + 75TiO_2 +10H2, containing nanoparticles and hydrogen gas, achieves 92 bar ICP at 252º.

Nanoparticles in biodiesel mix boost HRR by 20.2% and hydrogen by 19.3% over SBOB15. SBOB15 + 75TiO_2 +10H2 increases HRR readings by 6% over neat diesel. Results indicate a reduced igniting delay period with improved load conditions. Biodiesel mix SBOB15 + 75TiO_2 +10H2 decreases ID time by 12.15% compared to diesel with TiO_2 nanoparticles and hydrogen gas.

Based on these results, it seems that a biodiesel blend with hydrogen enhanced and nanoparticles added can outperform regular diesel in CI engine applications.

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Authors Contribution Statement

M. Prabhahar: Conceptualization, Investigation, data collection, Formal Analysis and Writing - original draft. S. Prakash: Data collection. Supervision, Writing – review & editing. P. Boobesh Kumar: Conceptualization, Writing – review & editing. B. Kalidhasan: Writing – review & editing. All the author's read and approved the final version of the manuscript.

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Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

Competing Interests

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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