Performance Analysis of Diesel Engine Fueled with Pine-Diesel Blends Enhanced by Al_2O_3 Nanoparticles

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Abstract

This study examines the effect of alumina (Al_2O_3) nanoparticles addition on a single cylinder, four stroke diesel engine fueled with pine-diesel biodiesel blends. The test fuel studied were a blend of 20% pine oil and 80% diesel (B20) containing 25, 50 and 75 ppm Al_2O_3 nanoparticles as an additive. The experimental test was conducted at different compression ratios of 15 and 17 in various loading conditions. While the thermochemical properties of the blended fuel were tested at central laboratory of Nepal Oil Corporation using standard methods and the results were found to be comparable to those of commercial diesel. According to performance evaluation, all fuel samples showed an increase in indicated power with increasing engine load. Both diesel and B20 fuel are outperformed by the B20+75 ppm test fuel blend, which produces the maximum indicated power of 4.49 kw at high load. This enhancement is connected to improved fuel atomization and improved combustion that the nanoparticles encouragement in diesel engine. All blends doped with nanoparticles showed a decrease in brake specific fuel consumption (BSFC) with increasing load; the B20+75 ppm fuel blends at CR 17 had the lowest BSFC of 0.30 kg/kWhr at high load, a 10% decrease from CR 15. With the load and compression ratio increase, brake thermal efficiency (BTE) increased up to 23.86% at high load for the B20+75 ppm blend at CR 17, which is about 4.42% more than commercial diesel. All things considered, adding Al_2O_3 nanoparticles to pine-diesel biodiesel blends greatly enhanced engine performance and combustion characteristics without necessitating any engine modifications. These findings demonstrate the potential of Al_2O_3 Nano-additives as a practical strategy for raising the effectiveness and fuel economy of compression ignition engines that run on biodiesel.
Keywords: Al_2O_3 nanoparticles, Blended fuel, Diesel engine, Engine performance, Pine oil

1. Introduction

Growing energy demand, depletion of fossil-fuel reserves, fluctuating petroleum prices, and stringent emission standards have driven extensive research into renewable fuels and fuel additives suitable for compression-ignition engines. Biofuels have gained importance as suitable substitute for diesel because of their renewable origin and wide availability. Biofuel are considered suitable alternatives for CI engine because they are widely accessible and can be produced from renewable sources (Tamilselvan & Nallusamy, 2015). According to (Shirneshan, 2013) , rapid economic growth, energy consumption has been rising rapidly many regions, particularly in Asia and the middle east making, India the fourth largest consumer globally, after China, USA and Russia. (Shirneshan, 2013) also notes that nearly 29.45% of the world's primary energy still comes from crude oil and rising concerns regarding fossil-fuel depletion and environmental impacts have pushed researchers towards viable green alternatives. Plant derived fuels such as methanol, ethanol and essential oils contain oxygenated compounds, which facilitate more efficient and complete combustion (Anand, Saravanan, & Srinivasan, 2010). Since the CO_2 released during combustion originates from biomass, biofuels contribute minimally to net carbon emissions. Pine oils used as fuel are generally categorized as triglyceride oils and terpene-based oils. While triglyceride oils are obtained from seeds, terpene oils such as eucalyptus and pine are extracted from other plant parts (Tamilvendhan & Ilangovan, 2011). Pine oil exhibits several fuel characteristics comparable to diesel, allowing it to be used on its own or mixed with diesel (Shyam, 1984).

Nanoparticles have recently emerged as effective additives for improving fuel thermal conductivity and combustion characteristics(S. Ekab et al., 2023). Their large surface-area to volume ratio of nanoparticles enhance heat transfer, shorter the ignition delay period and promotes more effective mixing of fuel and air (Venkatesan et al; 2017). Many studies confirm that nanoparticles-enriched fuels improved performance and reduce harmful emissions (Venkatesan et al., 2017; Khan et al., 2022). Although nanoparticles may slightly raise viscosity or density, their catalytic activity generally enhance ignition quality and improves combustion stability (Duan et al., ; Lawrence et al., 2022). Nanoparticles can also promote micro-explosion effects in fuel emissions, improving atomization and heat release (Dhahad et al., 2022). Previous findings showed significant reduction in CO_2 emissions and BSFC when Al_2O_3 nanoparticles were added to diesel (Sathiamurthi et al., 2019). Researchers who introduced 0.5 g and 1 g nanoparticles into conventional diesel fuel line where applying a magnetic field. Their results showed that CO_2 emissions decreased by 52% and 57 % respectively compared to conventional diesel fuel. In absence of magnetic field, the addition of the same nanoparticles quantities still lowered CO_2 levels by 22% and 52% though the reduction was less significant. Furthermore, when 0.5 g of nano-Al_2O_3 was used along with a magnetic field, the brake specific (BSFC) decreased by 13% relative to pure diesel, whereas the 1 g dosage resulted in a 7% reduction under the same conditions (Sathiamurthi, Vinith, & Sivakumar, 2019).

(Purushothaman & Nagarajan, 2009) evaluated the performance of orange oil when used as fuel in a compression ignition engine. The researchers found that orange oil combustion was characterized by a longer ignition delay and extended combustion duration compared with conventional diesel fuel. At full load, the brake thermal efficiency (BTE) achieved with orange oil was 31.7%, which was slightly higher than the 29.3% obtained with diesel. The study also reported a higher heat release rate for orange oil and notably lower emissions of HC, CO, and smoke relative to diesel. However, the use of orange oil resulted in an increase in NOx. In another study connected by (Muthusamy, Nallathambi, Ramasamy, & Mohamed, 2018) evaluated blends of pongamia biodiesel with Fe_3O_4 nanoparticles at dose level of 50 ppm and 100 ppm. The results indicated that addition of these nanoparticles improves brake thermal efficiency (BTE), reduced brake-specific fuel consumption (BSFC) and contributed to substantial decreased in unburned hydrocarbons, smoke, and carbon monoxide emissions. Also, (Hariram & Shangar, 2015) examined the combustion process under the influence of different compression ratios and overall performance of a direct-injection CI engine. The result from this work demonstrated that reducing compression ratio increase led to increase in brake-specific consumption and also caused the exhaust gas temperature to rise. On the other hand, the brake thermal efficiency decreased as the compression ratio was lowered.

Similarly,(Raman et al., 2013) investigated the combustion behaviour and emission profile of the diesel engine operating on the pine-oil biofuel in combustion along with selective catalytic reduction (SCR) and a catalytic converter. Their finding proved that brake thermal efficiency increased with increment of pine oil content in the fuel blend. They further found key reductions smoke, by 70.1%, CO by 67.5% and HC by 58.6% compared to conventional diesel fuel. These findings as well as the results of other studies indicate that performance characteristics of biofuels are similar to diesel. Base on this understanding, the present work focuses on evaluating the practicality of using pine-diesel blends enhanced with Al2O3 nanoparticles in a direct-injection CI engine, without requiring major engine modifications, and assessing their overall performance behavior.

According to the studies conducted by (Poudel et al., 2023), the addition of 90 ppm Fe_2O_3 nanoparticles in B20 pine-diesel blend resulted in a remarkable improvement in the performance of the engine. Their experiments conducted on variable compression-ratio diesel engine (CR 15 and 16) indicated improvement in may important parameters such as indicated power and brake power, thermal efficiencies, mechanical and volumetric efficiencies coupled with a significant reduction in specific fuel consumption. Overall, their findings indicate that Fe_2O_3 nanoparticles may be able to effectively improve combustion quality and operational efficiency pine-diesel biodiesel blends.

2. Methodology

2.1 Characterization of pine oil

Pine trees grow to a heights of about 40 meters, and possess a flat crown, reddish-brown fissured bark, and gray-green needle like leaves which generally occur in pairs (Tamilselvan & Nallusamy, 2015). They also produced orange-yellow flowers and pointed brown cones, and are grown as one of the commercial timber species. Pine oil, extracted from pinus sylvestris, is obtained by steam distillation from the needle, twig, and cone of tree. The oil is pale yellow in color, with a forest-like smell, and contains alcoholic compounds. The physical condition of the oil is watery. The major constituents of pine oil are α-terpinen and 3-carene. In the present study, pine oil obtained from Divya Rosin and Turpentine Pvt. Ltd was examined as a possible renewable fuel for application in a compression ignition engine. Table 1(Tamilselvan & Nallusamy, 2015) comprised pine oil properties with as compared to that of conventional diesel fuel. The data shows that pine oil has a higher calorific value than diesel, while kinematic viscosity and flash point are lower. Generally, its fuel properties show similarity to conventional diesel.

Table 1: Comparing of key fuel properties for diesel and pine oil

Properties	Diesel fuel	Pine oil
Density (kg/m^3)	830	846.3
Kinematic viscosity(mm^2/s) @40℃	3.2	1.8
Flash Point (℃)	63	46
Calorific Value (kJ/kg)	42,500	43,012
Cetane Index	49	14

2.2 Preparation of test fuel blend

The experimental test fuel samples were prepared by a two-step procedure with the aim of achieving stable and uniform nanoparticles dispersion. First, the base fuel blend (B20) was prepared by mixing 20% refined pine oil volumetrically, which is selected for its renewable nature and known ignition characteristics improvements, at 80% conventional diesel, as shown by (Venkataraman & Subramanian, 2022). In this base fuel blend aluminum oxide (Al_2O_3) nanoparticles were added at three concentration levels: 25 ppm, 50 ppm and 75 ppm by mass. For the present work, the required amount of Al_2O_3 nanoparticles was prepared by sol-gel method in the laboratory followed by (Owolabi & Ojadi, 2023), and their size, purity and crystalline structure were verified by using XRD analysis.

Following established nanofluid preparation procedures, the Nano additives were initially mixed in the fuel using a magnetic stirrer for 30 minute to break up an early agglomeration. This step was followed by a 60 minute controlled ultrasonication treatment, during which the sample container was placed an ice bath to minimize thermal evaporation (Pourhoseini & Ghodrat, 2021*)*. Ultrasonication ensured that the nanoparticles were evenly distributed and remained stable meaning they resisted settling or clustering over time. The fuel mixtures prepared for engine testing included B20 blended with 25 ppm, 50 ppm and 75 ppm of Al_2O_3 nanoparticles.

2.3 Experimental setup and procedure

The experimental work was performed using a computerized, single-cylinder, four-stroke, water cooled DI diesel engine equipped with a variable compression ratio mechanism and rated power 3.5 Kw at IOE, Thapathali campus, Kathmandu. To establish reference operating conditions, the engine was initially run on conventional diesel fuel at compression ratio CR 15 and fixed speed of 1500 rpm for about 25-30 minute until stable operation was maintained at roughly 1 atm, which was monitored through the built in pressure gauge. After the baseline run, the engine was tested using each of the prepared fuel blends B20+25 ppm, B20+50 ppm and B20+75 ppm fuels. An eddy current dynamometer was employed to apply adjusted in increment of 3 kg load corresponding to 1, 3, 6 and 9 kg, while maintaining the speed at 1500 rpm. Performance parameters for each fuel blend were recorded at compression ratio 15:1 and 17:1. The same procedure was repeated using diesel fuel to obtain comparative data. The fuel consumption was measured with a burette and stopwatch arrangement, noting the volume of fuel used over 60sec. The detail specifications of the experimental engine are presented in Table 2.

Table 2: Engine specifications

Features	**Specification**
Manufacturer	Kirloskar diesel engine
Engine type	Water Cooled Diesel, 4 Stroke
Number of Cylinder	1
Starting method	Electric motor cranking
Combustion process	Compression ignition
Load application	Eddy current dynamometer
Crank radius	55 mm
Adjustable compression ratio	15:1 to 18:1
Connecting rod length	300 mm
Maximum operating speed	1500 rpm
Rated power	3.5 kW

3. Results and Discussion

3.1 Thermochemical properties of test fuel

The thermochemical characteristics of the prepared fuel blends were evaluated at the Nepal Oil Corporation laboratory in Sinamangal, Kathmandu, following the standard testing procedure. The measured values are presented in Table 3. Overall, the obtained thermochemical properties of blended fuel showed good agreement with those of conventional diesel fuel.

Table 3: Thermochemical properties of test fuel

Parameters	Test Method	Diesel	B20	B20+50 ppm
Density at 15°C, kg/m^3	ASTM D1298	810-845	840	842
Flash Point, °C (Min)	IP 170	57	42	44
Cetane Number (Min.)	IP380/NS 237	46	51	52
Pour Point (°C)	ASTM D5949	-25	-10	-15
Kinematic Viscosity@40°C, (Cst)	ASTM D445	2-2.45	2.268	2.15
Calorific Value, (Kcal/kg)	IS 1448	11110	11214	11300

3.2 Brake specific fuel consumption (BSFC)

The Fig. 2 and 3 illustrate the variation of brake specific fuel consumption (BSFC) with engine load for diesel and the different test fuel blends at compression ratio (CR) of 17 and 15. For both diesel and biodiesel blends, BSFC consistently decreases as the load increases. This occurs because brake power rises more rapidly with load than the corresponding increase in fuel consumption, as also reported by (Ramadhas, Muraleedharan, & Jayaraj, 2005). Across all operating conditions, each fuel blends shows lower BSFC compared with diesel.

At CR 17, the B20+75 ppm fuel blend demonstrates about a 10 % reduction in BSFC at 9 kg load compared with its performance at CR 15. For the B20 blend, BSFC at high load is reduced by 5.26% and 2.56% relative to diesel at CR 17 and CR 15 respectively. At lower loads, the same test fuel blend achieves reduction of 3.14% and 2.12 % over diesel. These improvements can be attributed mainly to the reduced viscosity and increased calorific value introduced by nanoparticles (Yusof et al., 2020). Under full-load conditions, the BSFC values for commercial diesel at CR 17 and 15 were 0.38 and 0.39 Kg/kWhr respectively. For B20, the BSFC values were 0.36 and 0.38 Kg/kWhr, for B20+25 ppm, the values were 0.34 and 0.36 Kg/kWhr, for B20+50 ppm, 0.31 and 0.35 Kg/kWhr and for B20+75 ppm, 0.3 and 0.33 Kg/kWhr. Among all tested fuels, B20+75 ppm achieved the lowest BSFC at both compression ratios. This reduction is due to the addition of nanoparticles into biodiesel enhance the thermal conductivity of the fuel, shorten the ignition delay, and improve combustion efficiency, which lowers fuel consumption at given load (Ekab et al., 2023)

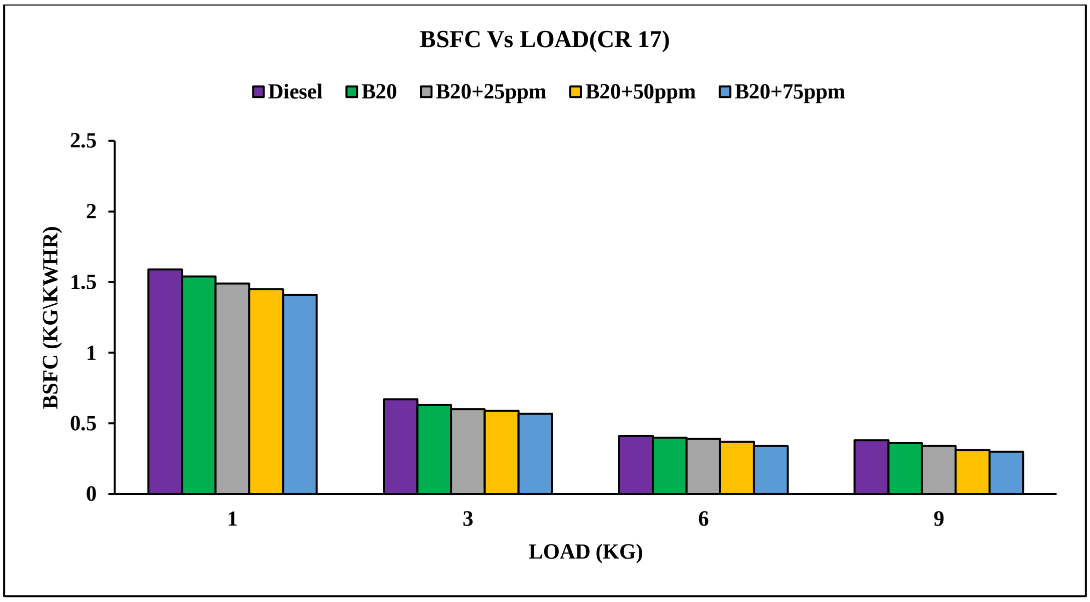

Fig. 1: Brake specific fuel consumption with varying load at CR 17

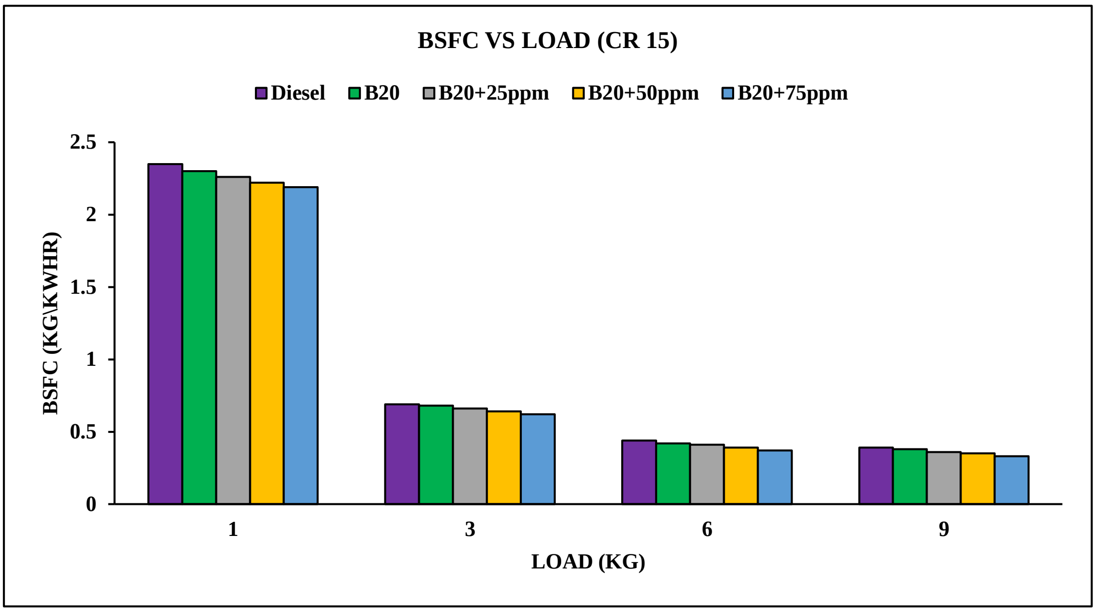

Fig. 2: Brake specific fuel consumption with varying load at CR 15

3.3 Brake thermal efficiency (BTE)

Brake thermal efficiency (BTE) indicate how effectively an engine converts the chemical energy of fuel into useful brake power. Figure 3 and 4 show how BTE vary with engine load as different fuel mixtures are used. In every loading condition, BTE increases as the load rises, mainly because higher loads reduce heat losses and allow the engine to produce greater power (Tamilselvan & Nallusamy, 2015). The BTE of all pine-diesel biodiesel blends with Nano additives at all loads performs better than that of commercial diesel. This improvement can be attributed to better atomization, enhanced fuel vaporization and more efficient combustion resulting from the lower viscosity of the fuel blends (Devan & Mahalakshmi, 2009).

At a compression ratio of 17, the BTE values for diesel, B20, B20+25 ppm, B20+50 ppm and B20+75 ppm were 22.85%, 23.52%, 23.62%, 23.71% and 23.86% respectively at high load. At CR 15, corresponding BTE values were 22.43%, 22.53%, 22.63%, 22.77% and 22.86%. This indicates that at CR 17, commercial diesel and the nanoparticles enriched biodiesel blends achieved BTE improvements of 1.87%, 4.39%, 4.37%, 4.12% and 4.37% respectively when compared to their performance at CR 15. The observed enhancement is attributed to the additional oxygen available in the nanoparticles enriched fuel which support more complete combustion and also nanoparticles provide large surface to volume ratio, promoting a more uniform mixture and improved fuel burning (Devarajan, Munuswamy, & Mahalingam, 2019*)* and due to the higher calorific value of pine oil (Joshi & Adhikari, 2021).

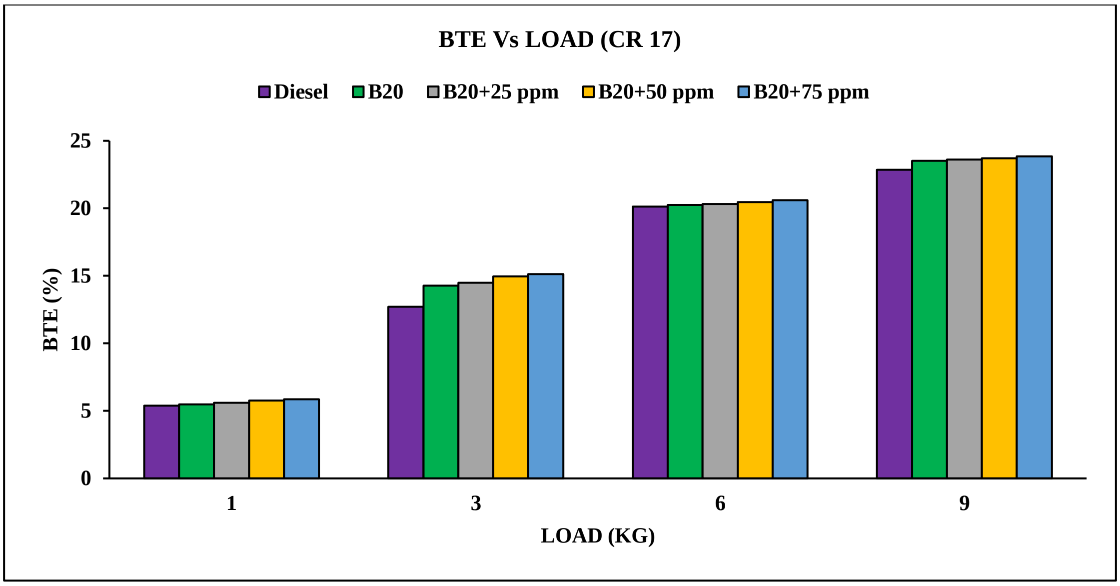

Fig. 3: Brake Thermal efficiency with varying load at CR 17

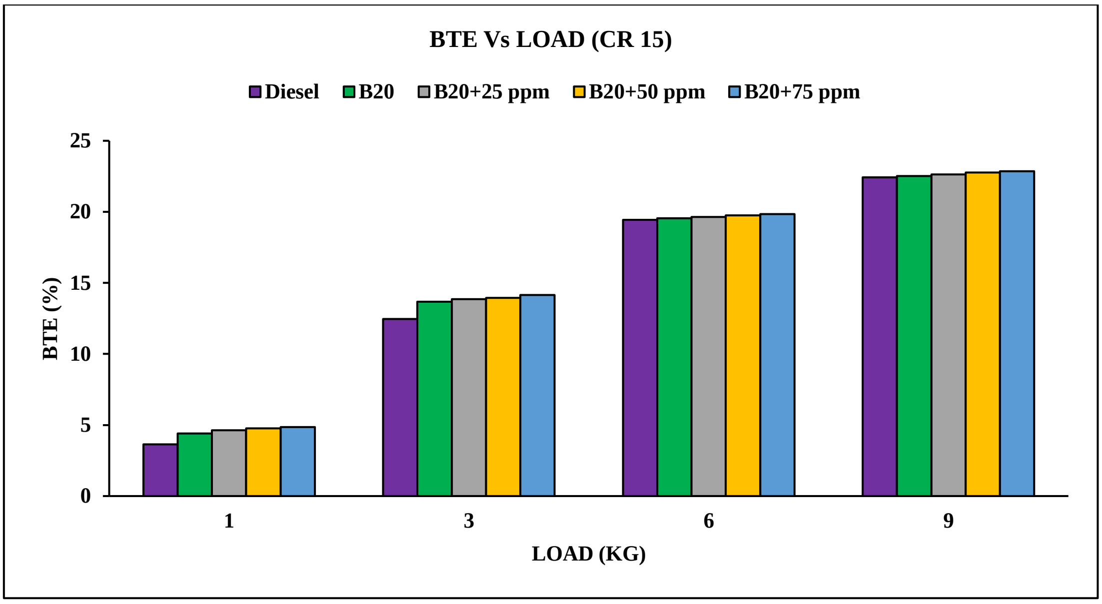

Fig. 4: Brake Thermal efficiency with varying load at CR 15

3.4 Indicated power (IP)

Figure 5 and 6 illustrates the variation of IP with load for diesel and pine oil blends with Nano-additives at different compression ratios at 15 and 17. The value of IP increase with increase in load in all cases. At both CR (i.e. 17 and 15), B20 showed a slightly higher IP compared to commercial diesel, this is due to the presence of inherent oxygen in pine oil, which improves combustion efficiency and heat release rate (Agarwal, 2007). The addition of Al_2O_3 nanoparticles further enhanced brake power, with the maximum value observed for B20+75 ppm of 4.49 KW at 9 kg load, which was higher than both diesel and B20. This enhancement is explained by the catalytic role of Al_2O_3 nanoparticles, which promote atomization, accelerate oxidation reactions and improve the combustion rate due to their high surface to volume ratio(Karthikeyan, Elango, & Prathima, 2014). At CR 17 IP is consistently higher than CR 15, for B20+75 ppm fuel blend at lower load with improvements of about 21.71% and higher load 20.37%. This shows that the effect of higher compression ratio on IP is more significant at lower load. Among the tested fuels, the B20+75 ppm blend always gives the highest indicated power, underlining the positive effect of increased nanoparticle concentration on in-cylinder energy conversion.

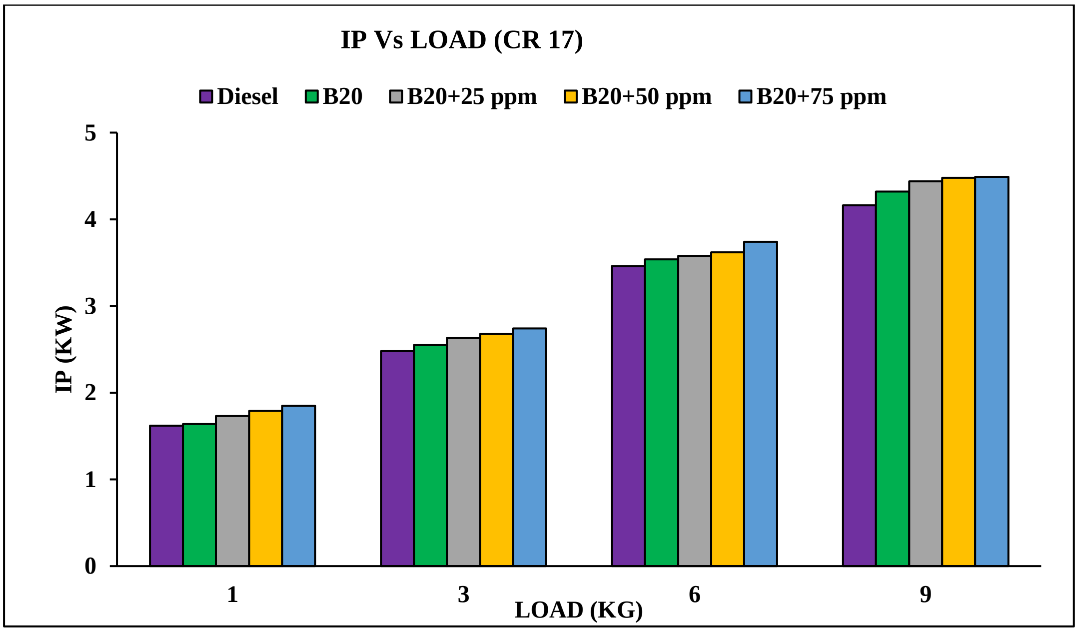

Fig. 5: Indicated power with varying load at CR 17

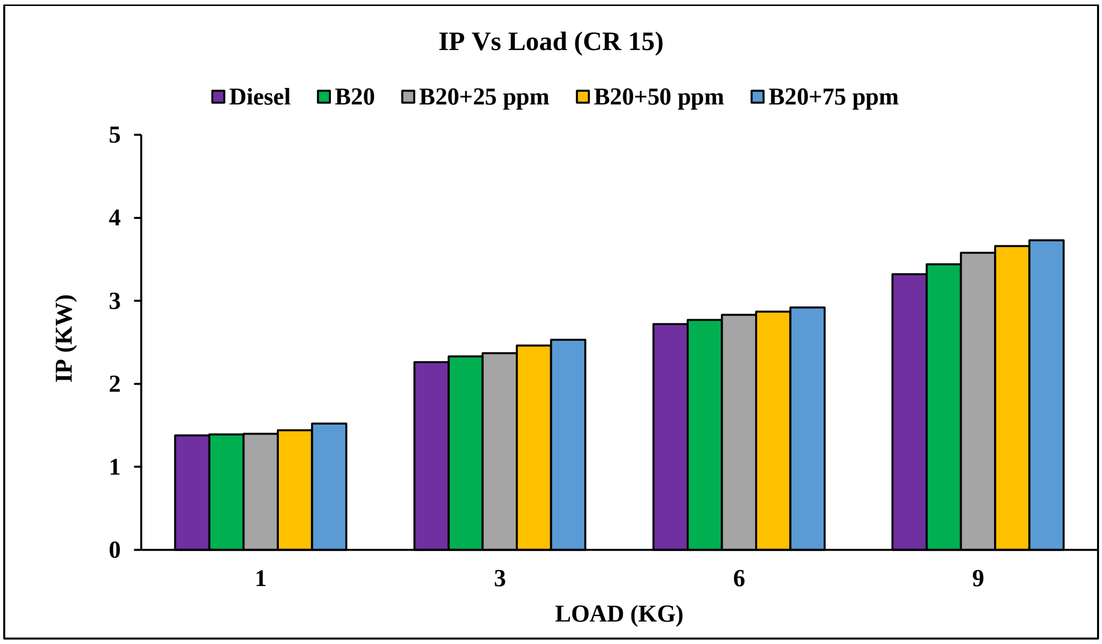

Fig. 6: Indicated power with varying load at CR 15

4. Conclusion

In this work, pine oil was examined as renewable substitute fuel for compression-ignition engine. The tests were carried out at two compression ratios CR 15 and 17. Using an ultrasonication process, Al_2O_3 nanoparticles were added to the B20 fuel at 25 ppm, 50 ppm, and 75 ppm concentrations.

Accordingly, B20, B20+25 ppm, B20+50 ppm and B20+75 ppm blends were prepared. The major findings obtained from the experimental work are summarized below

1. In every blend tested, the BSFC values recorded were always below those of conventional diesel fuel under different load conditions.
2. For a compression ratio of CR 17, the B20+75 ppm blend of fuel exhibited a reduction of 10 % in BSFC at higher load compared to its performance at a compression ratio of CR 15.
3. The BTE of all pine-diesel biodiesel blends with Nano additives at all loads performs better than that of commercial diesel.
4. At CR 17, commercial diesel and the nanoparticles enriched biodiesel blends achieved BTE improvements of 1.87%, 4.39%, 4.37%, 4.12% and 4.37%, when compared to their performance at CR 15
5. At both CR (i.e., 17 and 15), B20 depicted a slightly higher IP than that of commercial diesel, because of the presence of inherent oxygen in pine oil that improves combustion efficiency and heat release rate.
6. With the addition of Al_2O_3 nanoparticles, indicated power further improved; the maximum value of B20+75 ppm was 4.49 KW at 9 kg load, which is higher than diesel and B20.

The present study concludes that B20 blends with enriched Al_2O_3 nanoparticles can act as a promising alternative fuel for CI engine, enhancing the performance and giving better fuel efficiency. Looking ahead, there is every likelihood that biofuels could gradually substitute conventional diesel fuel, thus offering a sustainable alternative to meet ever-increasing energy requirements and the decreasing availability of fossil fuels.

Conflicts of Interest

The authors declare that there is no conflict of interest associated with this research work.

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