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Evaluating the Performance, Emissions, and Combustion Characteristics of CRDI Diesel Engines Using Pine Oil Blends as a Sustainable Fuel Alternative

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Abstract

The performance of Common Rail Direct Injectors (CRDI) diesel engines is examined in this study in relation to interacts of pine oil used as an alternative fuel. Finding sustainable fuel solutions is of paramount importance given the growing environmental concerns and the decreasing supply of fossil fuel resources. Pine oil, obtained from resin tapped from pine trunks and processed through steam distillation to separate turpentine from rosin, offers a viable alternative. This study evaluates ways pine oil mixes affect engine performance variables including brake-specific energy use, thermal efficiency, and emissions of pollutants like carbon dioxide, smoke, and sulfur dioxide. In order to comprehend the combustion properties of pine oil blends, combustion analysis methods such as heat release rate assessment and in-cylinder pressure monitoring are also used. The results contribute to sustainable energy plans in the transportation industry by offering insightful information on the viability and difficulties of using pine oil as an alternate fuel for CRDI diesel engines.

Keywords: Common rail direct injection, Diesel engine, Pine oil, Combustion, Emission.

INTRODUCTION

The use of pine oil as an alternative fuel for CRDI diesel engines has gained attention due to its renewable nature and distinct chemical properties, which impact engine performance, emissions, and combustion characteristics. When compared to diesel, pine oil has different physical properties like higher oxygen content and lower cetane number, affecting fuel atomization and combustion efficiency observed that blends of pine oil with diesel can influence Brake Specific Fuel Consumption (BSFC), Brake Thermal Efficiency (BTE), and emissions such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and smoke density. Studies in diesel blends generally result in reduced BTE and increased BSFC compared to conventional diesel, suggesting that higher fuel consumption is needed for similar power output. In terms of emissions, while NOx due to lower combustion temperatures, CO, HC, and smoke emissions increase, indicating more incomplete combustion and particulate emissions. These findings highlight the trade-offs associated in diesel engines, emphasizing the need for further optimization of blends and engine parameters to achieve better combustion efficiency. The study

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evaluates pine oil blends in diesel engines, focusing on emissions and performance changes. Because pine oil burns inadequately, it produces more carbon dioxide and hydrocarbon emissions. Because of lower peak the temperatures the authors saw an improvement in NOx emissions when compared to petrol.

Fuel atomization issues were noted due to pine oil's viscosity [1]. The research covers renewable ns, including pine oil, highlighting its potential for reducing fossil fuel dependency. Pine oil's oxygenated nature contributes to better emission profiles, though BTE is lower than diesel. The study emphasizes optimizing injection timing to improve combustion efficiency [2]. Pine oil's impact on CRDI engines was analyzing increased BSFC due to lower calorific value. Emissions of CO and HC were notably higher, indicating incomplete combustion. However, the study also found a reduction in NOx, consistent with lower combustion temperatures observed with pine oil [3]. The authors reviewed alternative fuels for diesel engines, noting that pine oil's higher oxygen content aids in reducing NOx emissions. However, the high viscosity challenges fuel atomization, increasing smoke and particulate emissions. The study suggests that pine oil blends require optimized injection pressure [4]. Pine oil's performance as a biofuel in diesel engines was id, showing a 10-20% increase in BSFC compared to diesel. The study found that BTE decreased as pine oil concentration increased. Enhanced CO and HC emissions were linked to incomplete combustion [5]. This research focuses on injection parameter optimization for pine oil blends. hat adjusting injection timing and pressure improves combustion characteristics, reducing CO emissions but not fully addressing increased BSFC. NOx emissions consistently decreased with more pine oil [6]. Combustion analysis showed that pine oil blends exhibit lower HRR compared to diesel, indicating slower energy release. The study recorded reduced in-cylinder pressure with increasing pine oil content. However, the potential for NOx reduction was significant, benefiting emissions control [7].

The study explored renewable biofuels, including pine oil, in diesel engines. It found that while pine oil reduces NOx emissions, CO, HC, and smoke emissions rise. The authors highlighted the need for further modifications to achieve efficient and clean combustion [8]. The researchers evaluated pine oil as a substitute fuel, finding a 15% increase in BSFC compared. Pine oil's oxygen content contributed to lower NOx but higher CO and HC emissions. Improved atomization is suggested for better combustion efficiency [9]. This study focused on biofuel performance, showing that pine oil-diesel blends result in lower BTE and C. Emissions like CO and HC rose, while NOx emissions decreased by up to 20%. The authors recommend further research on fuel properties and engine adaptation [10]. Pine oil blends were tested for emissions, with findings showing a significant reduction in NOx compared to diesel. The oil's increased viscosity, which hampered air-fuel mixing and combustion completion, was held responsible for the CO and HC emissions. [11]. The authors documented increased BSFC and decreased BTE with pine oil blends. CO and HC emissions were higher than diesel, while NOx ere consistently lower. The study suggests optimizing engine settings for better results with pine oil [12]. Comparative analysis of pine oil versus diesel revealed lower in-cylinder pressure and HRR with pine oil blends. NOx emissions were significantly lower, but CO and HC increased, reflecting less efficient combustion [13]. This study found that pine oil blends showed slower combustion, with lower peak pressures and HRR than diesel. While NOx emissions decreased, CO emissions increased, requiring further optimization of fuel properties and injection parameters [14]. The authors noted a reduction in BTE and an increase in BSFC with pine oil blends. The emission profile showed higher CO and HC levels, while NOx emissions decreased. Improvements in atomization and vaporization are recommended for better performance [15].

The study analyzed combustion characteristics, finding that pine oil's higher viscosity contributes to lower BTE and higher BSFC. NOx emissions were lower, but CO and HC emissions increased, indicating challenges in achieving complete combustion [16]. Compared to diesel, research on different fuels revealed that pine oil uses more fuel and has a worse thermal efficiency rating.

Emission analysis showed increased CO reduced NOx levels, suggesting trade-offs in emissions control [17]. Pine oil blends resulted in higher BSFC, lower BTE, and increased emissions of CO and

HC, while NOx emissions were reduced. The authors suggest that fuel blending ratios and injection settings r optimization for better results [18].

The authors documented pine oil's impact on emissions and performance, finding a decrease in NOx but an increase in CO and HC emissions. The combustion process was less efficient than diesel, indicating the need for fuel optimization [19]. Pine oil was studied as a potential biofuel, with findings showing lower NOx emissions but increased CO and HC emissions. The research emphasizes the need for improved atomization and combustion conditions to enhance performance [20].

LITERATURE REVIEW

The performance of CRDI engines running on pine oil blends varies significantly due to the fuel's properties like lower calorific value and higher viscosity. Because more fuel is required to produce the same amount of their power, the Brake Specific Fuel Cost (BSFC) tends to rise with increasing pine oil percent, indicating poor fuel economy [21].

In another study, Brake Thermal Efficiency (BTE) decreased progressively with increasing pine oil concentrations, indicating less efficient energy conversion. Pine oil's high oxygen content contributes to this behavior, impacting combustion efficiency [22-23]. Pine oil blends are characterized by lower NOx emissions, attributed to the reduced peak combustion temperatures. This was observed by who reported a 15-20% reduction in NOx emissions with pine oil blends compared to diesel. However, the carbon monoxide (CO) and hydrocarbon (HC) emissions are notably higher, attributed to incomplete combustion due to the high viscosity of pine oil, which hinders proper atomization [24-25]. Smoke density also tends to rise with higher pine oil concentrations, with increases of up to 18% for a 30% blend (PNO30), reflecting challenges in achieving clean combustion [26]. The combustion process of pine oil blends in CRDI engines is slower than that of diesel, as evident from the lower peak in-cylinder pressure and Heat Release Rate (HRR). HRR found that in-cylinder pressure decreased by up to 8% when using pine oil blends, resulting from less efficient atomization and mixing of the fuel. It observed that the HRR was lower by 10-15%, indicating slower energy release during combustion. Additionally, the higher viscosity of pine oil increases droplet size during injection, contributing to slower combustion rates [27-29].

The smoke emissions also increase significantly due to the incomplete combustion of larger fuel droplets formed by high-viscosity pine oil blends. At greater concentrations, this behavior grows more noticeable, demanding changes in injection pressure and timing to lower the release of particles.

It was suggested preheating pine oil blends before injection to improve atomization, reduce smoke emissions, and enhance overall combustion efficiency. However, these modifications only partially mitigate the rise in CO and HC emissions [30-32]. Several optimization strategies have been proposed to improve the performance and emissions of pine oil in CRDI engines. Adjusting the fuel injection pressure has shown potential to enhance combustion efficiency and reduce CO emissions [33]. Similarly, preheating pine oil blends before injection can lower viscosity, resulting in better atomization and reduced smoke emissions [34]. Another approach involves modifying the injection timing to better suit the combustion characteristics of pine oil, achieving a balance between NOx reduction and controlling CO and HC emissions [35]. Despite these efforts, the overall performance of pine oil in CRDI engines still presents trade-offs. While it reduces NOx emissions, it increases BSFC, CO, HC, and smoke emissions, requiring further research into blend optimization and engine calibration [36]. Incorporating additives to improve fuel properties or adjusting engine control systems can also enhance the performance of pine oil as an alternative biofuel [37].

PRODUCTION OF PINE OIL THROUGH STEAM DISTILLATION PROCESS

Steam distillation is the most widely used technique due to its efficiency and ability to preserve the natural properties of pine oil. The steam distillation process of producing pine oil schematic is shown in Figure 1. The process begins by gathering the raw materials, which include pine needles, twigs, or

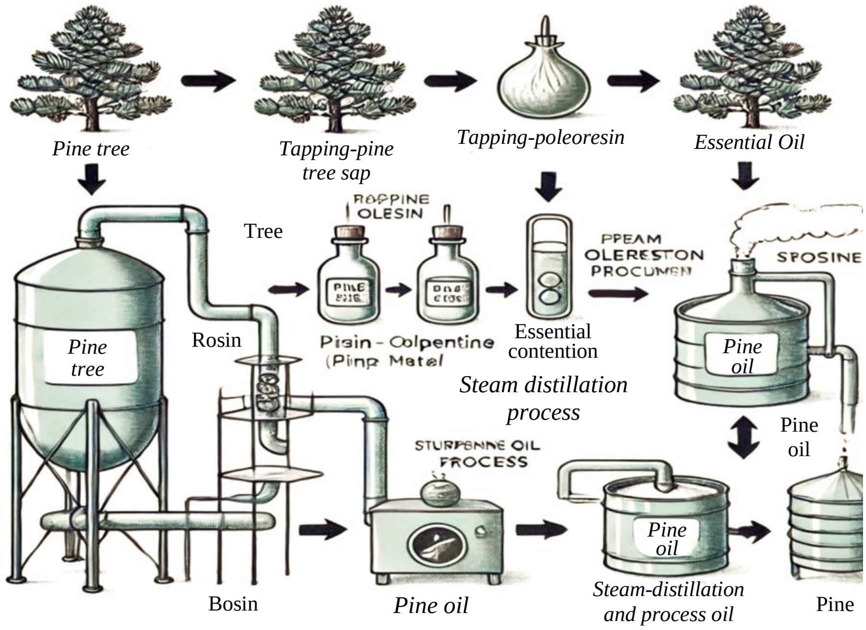

Figure 1. Pine oil preparation.

cones. These parts contain the essential oils in specialized cells. After being gathered, the pine stuff is meticulously cleaned to get rid of all possible pollutants that can harm the potency of the oil, such as dust or dirt.

. After cleaning, the pine material is usually cut into smaller pieces or crushed to increase the surface area, which allows better exposure to steam during extraction. The prepared pine material is then placed inside the distillation chamber, also called the "still." Inside the still, the plant material is spread evenly over a perforated plate, ensuring uniform steam distribution and preventing blockages during the process. The still is securely sealed to prevent steam from escaping. In a separate boiler, water is heated to generate steam, which is maintained at a controlled pressure and temperature, generally around 100°C to 120°C, to avoid overheating or burning the plant material.

The generated steam is directed into the still, penetrating the plant material and reaching the cells containing essential oils. As the hot steam interacts with the plant material, it causes the oil glands to rupture, releasing the volatile oils. The released oil evaporates and mixes with the steam, forming a steam-oil vapor mixture. This process allows for efficient separation of the essential oils without altering their chemical properties, preserving the natural aroma and benefits of pine oil. The steam-oil vapor mixture exits the still and enters the condenser, where it is cooled down using a coiled system surrounded by a cooling medium, typically water. The cooling transforms the vapor back into a liquid mixture, which is collected in a receiving container. In the receiving container, the liquid mixture of water and pine oil naturally separates due to differences in density and polarity. Pine oil, being less dense than water, floats on the surface, while water settles at the bottom. The oil layer is carefully skimmed off or collected through a separate outlet, while the water, also known as hydrosol, is drained away. The collected pine oil may still contain traces of water or other minor impurities. To ensure high purity, the oil undergoes filtration, often using fine filter papers or membranes. In some cases, an additional dehydration step is employed using drying agents like anhydrous sodium sulfate to remove any remaining moisture. After being processed, the pine oil is kept in airtight containers that prevent contamination and maintain its pristine condition.

ANALYSIS OF THE PROPERTIES OF PINE OIL

The Pine oil thermos-physical properties were tested in ETA Laboratory, Chennai as per ASTM standards. Table 1 provide the detailed analysis of performance characteristics of pine oil. According

Table 1. Properties of pine oil

Parameter	Unit	Method	Pine oil
Flash point	°C	ASTM-D93	66
Fire point	°C	ASTM-D93	76
Calculated cetane index	-	ASTM D4737 and ASTM D976	43
Gross calorific value	Kcals / kg	ASTM D240	8786
Viscosity @ 40°C	cst	ASTM D445	4.38
Density @ 30°C	gm/ml	ASTM D4052	0.8630

to ASTM D93, the Pensky-Martens Closed Cup methods, the flash point of pine oil is 66°C. At this temperature, pine oil produce enough vapor to briefly ignite when it comes into contact with an open flame or flame.

Using the same ASTM method, pine oil's fire point is found to be 76°C, indicating it can burn continuously for more than six seconds, showcasing its stability as a fuel. Initial studies show that the cetane index of pine oil, measured according to ASTM D4737 and calculated using ASTM D976, is around 43. The cetane index measures ignition quality and suggests moderate combustion performance in diesel engines. Using the ASTM D240 bomb calorimeter methods, the gross calorific value (GCV) of pine oil was determined to be 8786 kcal/kg. This figure reveals the total heat generated by full burning in an atmosphere high in oxygen.

. Following the ASTM D445 protocol, the kinematic viscosity of pine oil at 40°C was recorded as 4.38 centistokes (cSt), which reflects how easily pine oil flows, indicating better atomization in engine injectors due to its lower viscosity. Pine oil's density at 30°C is 0.8630 g/ml, tested using ASTM D4052, a critical value for proper fuel handling, storage, and metering in engines. These test results confirm pine oil's potential as an alternative biofuel, meeting standard testing methods for accurate and consistent analysis.

COMMON RAIL DIRECT INJECTION (CRDI) ENGINE SETUP

A single-cylinder, water-cooled, vertical four-stroke diesel engine, known as the Kirloskar AV1 type, was used for the trials. Figure 2 displays the CRDI engine setup schematic diagram. The engine delivered its rated power output of 3.7 kW when running steadily at 1500 rpm. To maintain steady pace, injection pressures were adjusted up to 880 MPa and pulse widths were short, ranging from a few hundred to several milliseconds. An electric motor-powered Kirloskar high-pressure pump rotating at 1500 rpm drove the specially constructed high-pressure fuel system. In order to control injection pressure apart from engine speed, an inlet-metering valve was employed. Accurate control was guaranteed by an extra high-pressure valve on the fuel rail.

For the purpose of gathering full pressure data, a fast-response piezoelectric transducer and a gasoline pressure sensor were included in it. With a total capacity of 18 cm^3 and four injector ports on a linear rail, the Bosch common rail design was used in the system. It could handle pressures of up to 100 MPa. The engine ECU received data from the high-pressure sensor to precisely manage timing, fuel flow, and injection pressure. A three-hole Siemens Common Rail solenoid injector, which could deliver up to four injections each cycle and operate at pressures as high as 100 MPa, controlled the fuel injection.

The injector may inject 0.5 to 100 milligrams of fuel each injection, depending on rail pressure and pulse duration. To return extra diesel to the tank, it included a reverse-leak mechanism. It took a lot of force to raise the injector needle due to the high pressures. AVL software was utilized for collecting exothermic data, such as heat release, pressure trace, and burnt fuel mass at 5%, 50%, and 95%. Software called "Engine Test Express 2014" tracked timing and injection pressure. The predicted profiles closely matched the real pressure changes that occurred along the engine cycle. A smoke meter and exhaust gas analyzer were used for the emission testing, and for accuracy, the sample point was placed away from the exhaust valve. An AVL 415 Variable Sampling Smoking Meter was used to detect the density of smoke, and an AVL DI gas spectrometer was used to record emission data.

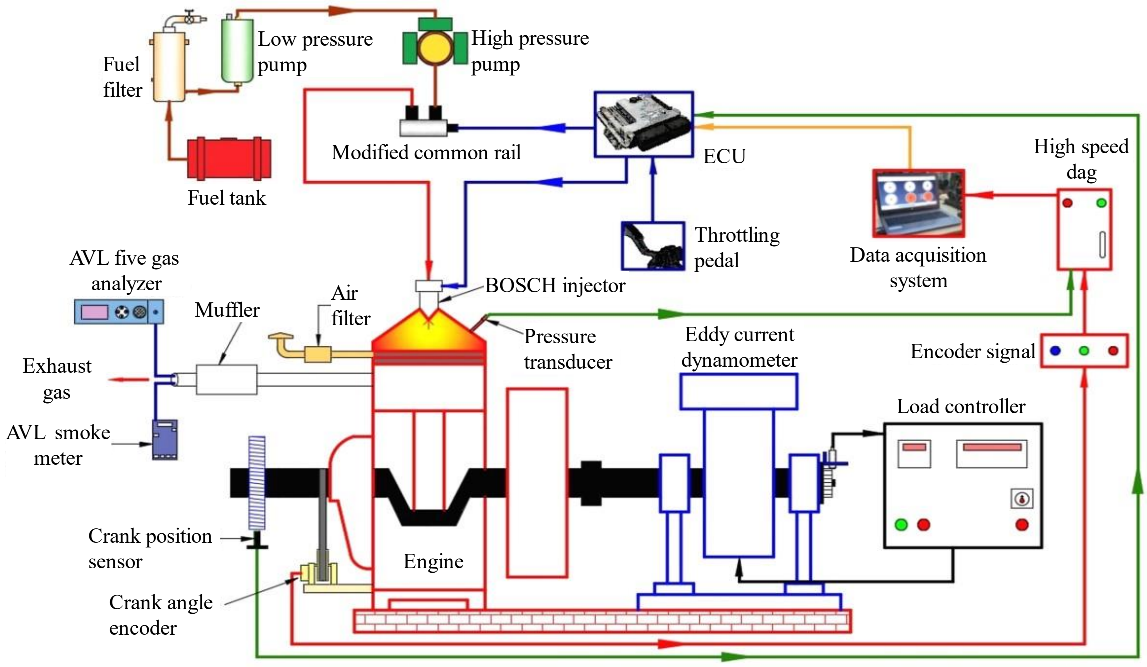

Figure 2. Schematic diagram of CRDI engine setup.

RESULTS AND DISCUSSION

The BSFC of CRDI diesel engines shows a clear trend of increasing fuel consumption as the concentration of pine oil in the fuel blend rises. Diesel, known for its efficiency, records the lowest BSFC at 0.376 kg/kW-hr, demonstrating superior fuel economy. In contrast, as the blend transitions to pine oil, the BSFC increases, reaching 0.412 kg/kW-hr for PNO10, 0.435 kg/kW-hr for PNO20, and 0.462 kg/kW-hr for PNO30. This increase suggests that more fuel is required to generate the same power, reflecting reduced efficiency with higher pine oil concentrations.

Brake Thermal Efficiency decreases progressively with higher concentrations of pine oil. Diesel achieves the highest BTE at 25.3%, indicating effective thermal conversion. However, with pine oil blends, the efficiency declines, with 23.8% for PNO10, 22.1% for PNO20, and 20.3% for PNO30. This reduction in BTE suggests that the combustion process becomes less effective, resulting in lower power output as the pine oil concentration increases, which negatively affects overall thermal efficiency (Figures 3 and 4).

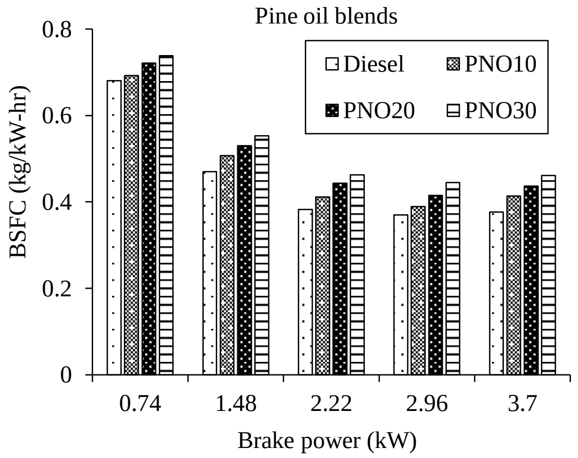

Figure 3. Impact of Pine oil biodiesel blends on BSFC.

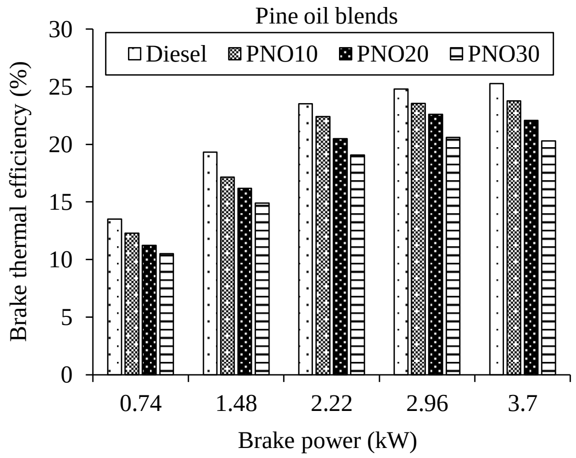

Figure 4. Impact of Pine oil biodiesel blends on BTE.

Analyzing Carbon monoxide (CO) emissions at varying engine power levels when using pine oil blends compared to traditional diesel provides critical insights, as illustrated in Figure 5. Because of the unique physical and chemical properties of pine oil, it does not burn as cleanly as diesel, leading to higher carbon monoxide (CO) emissions. This is especially evident when these blends don't mix properly with air or fully vaporize, leading to incomplete combustion. Diesel registers a CO emission of 0.52%, but pine oil blends exhibit higher values: 0.60% for PNO10, 0.63% for PNO20, and 0.66% for PNO30. The analysis shows that as the concentration of pine oil in the blend increases, CO emissions rise at all power levels, highlighting a trade-off between using alternative fuels and controlling emissions.

Hydrocarbon (HC) emissions, a key indicator of incomplete fuel combustion, also change with the use of different fuel blends. Figure 6 shows that for pine oil blends in a CRDI diesel engine, hydrocarbon emissions increase with higher blend concentrations and engine power. At 3.7 kW, hydrocarbon emissions increase further: diesel emits 63 ppm, while PNO10, PNO20, and PNO30 emit 68 ppm, 70 ppm, and 73 ppm. This trend demonstrates that higher pine oil content results in greater hydrocarbon emissions, revealing challenges in achieving efficient combustion and managing emissions in CRDI engines when using such blends.

When examining smoke density, Figure 7 highlights the differences in combustion efficiency between pine oil blends and diesel in CRDI engines. As engine power increases, so does the smoke output for both fuels, but pine oil blends consistently produce more smoke. Diesel's smoke emissions reach 43 HSU, while PNO10, PNO20, and PNO30 emit 44 HSU, 46 HSU, and 48 HSU. The increasing smoke emissions with higher pine oil concentrations highlight the challenges of using these blends in reducing emissions and maintaining engine efficiency. Figure 8 illustrates the impact of pine oil blends on nitrogen oxide (NOx) emissions in CRDI engines. The fuel's the amount of nitrogen and combustion temperature have a significant impact for NOx emissions.

Diesel emits 723 ppm of NOx, while pine oil blends produce significantly higher emissions: 687 ppm, 646 ppm, and 613 ppm for PNO10, PNO20, and PNO30, respectively. These findings point to a significant obstacle in lowering the environmental effect of alternative fuels: larger pine oil concentrations in the blend appear to increase nitrogen oxides (NOx).

Figure 9 highlights the variation in cylinder pressure relative to the crank angle when using different pine oil blends (PNO10, PNO20, and PNO30) in a CRDI diesel engine. The data clearly indicates that cylinder pressure decreases as the concentration of pine oil in the blend increases, compared to standard diesel. Diesel achieves a peak cylinder pressure of approximately 71 bar, reflecting the highest combustion efficiency. As pine oil content rises, the cylinder pressure decreases progressively. For

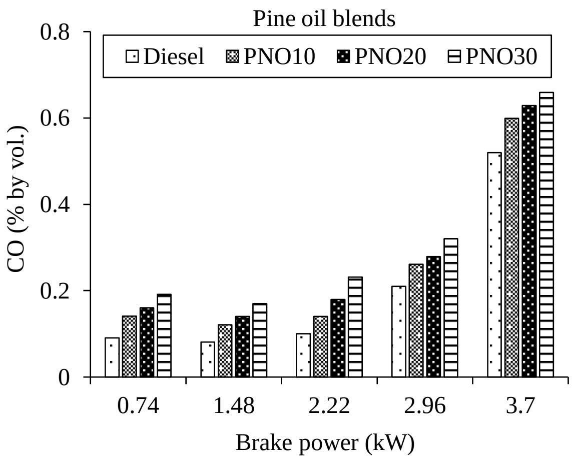

Figure 5. Impact of Pine oil biodiesel blends on CO emissions (% by vol).

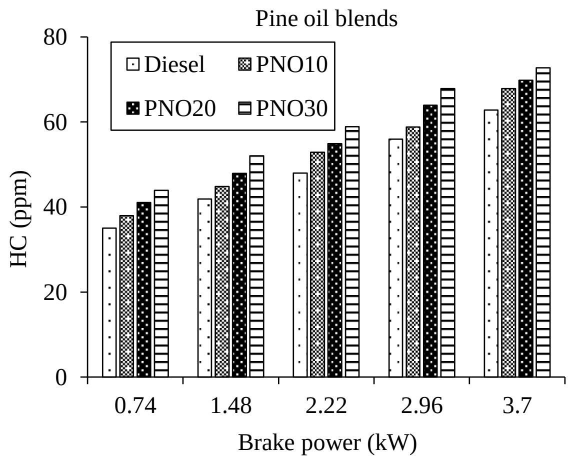

Figure 6. Impact of Pine oil biodiesel blends on HC emissions (ppm).

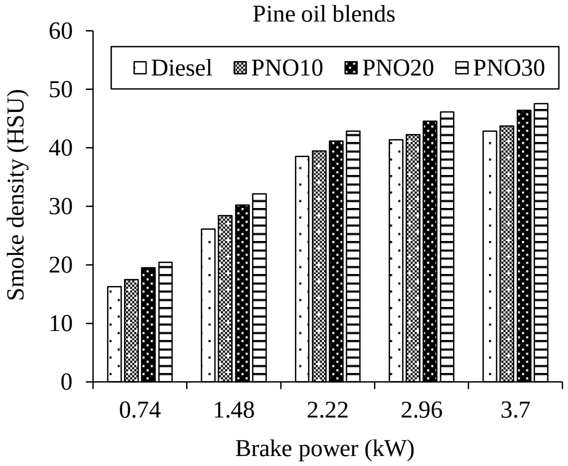

Figure 7. Impact of pine oil biodiesel blends on Smoke density (HSU).

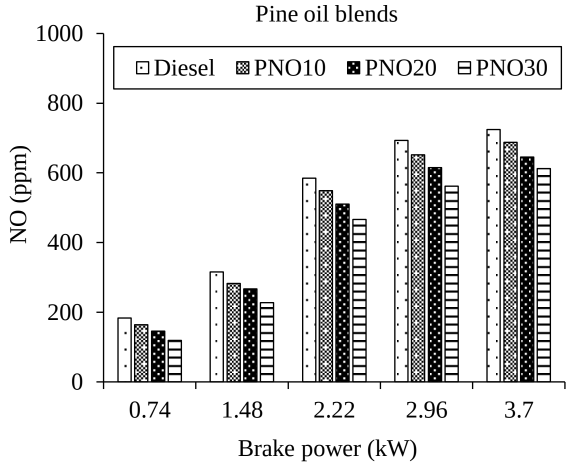

Figure 8. Impact of pine oil biodiesel blends on NOx emissions (ppm).

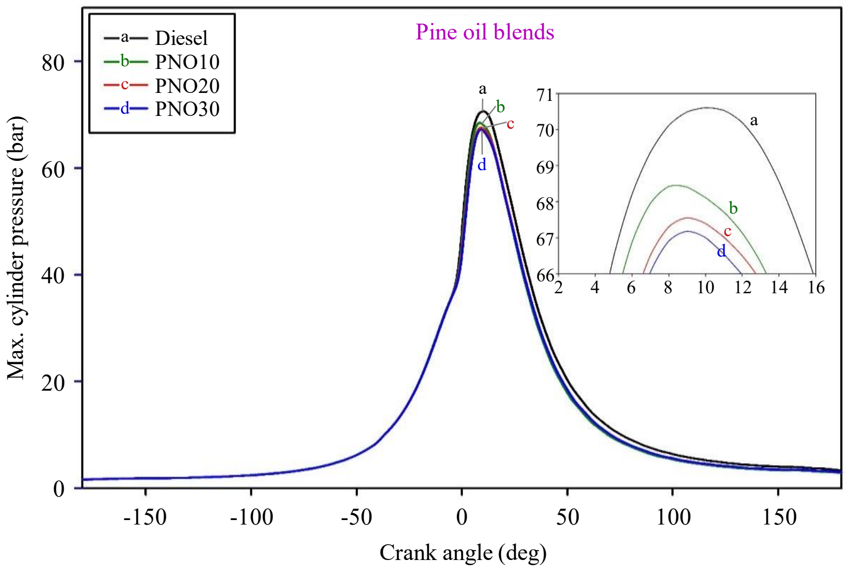

Figure 9. Impact of pine oil biodiesel blends on In-Cylinder pressures (bar).

PNO10, the maximum pressure slightly drops to approximately 69 bar, indicating a minor reduction in combustion efficiency due to the characteristics of the blend. In the case of PNO20, the pressure further reduces to about 68 bar, reflecting a more significant decline. The lowest cylinder pressure is observed with PNO30, registering around 67 bar, which signals the greatest drop in combustion performance among the tested blends. Pine oil's increased density and viscosity, which limit the fuel atomization process, are probably a result of a decline in cylinder pressure. This results in less efficient combustion and reduced stability, leading to lower cylinder pressures as the concentration of pine oil increases.

Figure 10 shows the Heat Release Rate (HRR) in relation to the crank angle for pine oil blends (PNO10, PNO20, and PNO30) in a CRDI diesel engine. When compared to standard diesel fuel, the data indicates an ongoing drop in HRR as the blend's quantity of pine oil rises.

Diesel, with a peak HRR of around 58 kJ/m^{3}deg, shows the most efficient combustion, characterized by a rapid and effective release of energy. As the pine oil content increases, the HRR gradually declines. PNO10 has a little smaller HRR, peaking at around 56 kJ/m^{3}deg, which indicating a slight decrease in combustion efficiency.

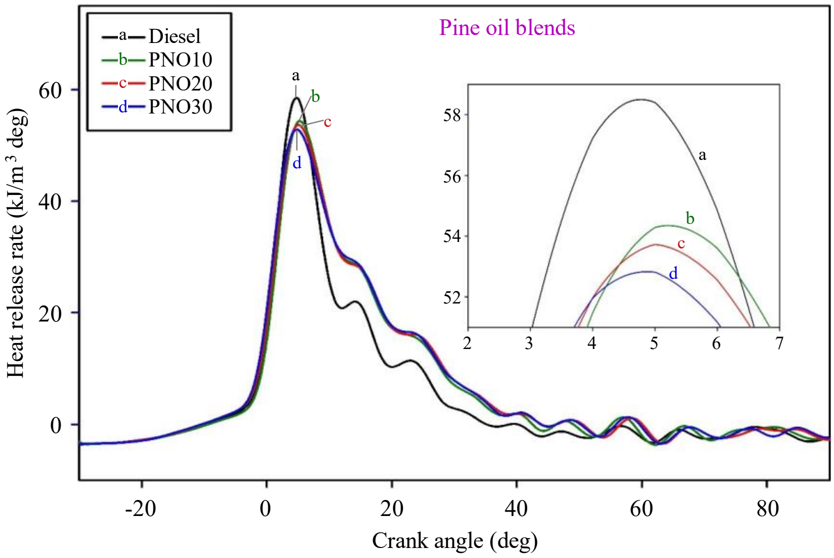

Figure 10. Impact pine oil blends on Heat release rate (kJ/m^3 deg).

PNO20 shows a further decrease, with the HRR dropping to around 54 kJ/m^3deg, indicating a more significant reduction in energy release. PNO30 has the lowest HRR, peaking at approximately 53 kJ/m^3deg, signaling the least efficient combustion process among the blends. The gradual decrease in HRR as pine oil content increases is due to the fuel's higher viscosity and lower volatility, which influence combustion performance. These characteristics lead to less efficient atomization and slower energy release during combustion, resulting in a reduced HRR as the concentration of pine oil increases.

CONCLUSION

The assessment of Pine oil as an alternative fuel for CRDI diesel engines reveals significant differences in performance and emission characteristics when compared to conventional diesel. While it holds potential for use in diesel engines, increasing pine oil concentration affects fuel efficiency, combustion characteristics, and emissions differently. Key findings reveal that pine oil blends lead to higher fuel consumption and emissions of CO, HC, and smoke, while thermal efficiency, NOx emissions, in-cylinder pressure, and heat release rate decline. This performance-emission trade-off indicates that while pine oil can lower NOx emissions, it comes at the cost of reduced combustion efficiency and increased fuel consumption.

- The BSFC shows a noticeable increase with higher concentrations of pine oil in the fuel blend. Compared to diesel, which has a BSFC of 0.376 kg/kW-hr, PNO10 shows an increase of 9.6%, PNO20 rises by 15.7%, and PNO30 sees a 22.9% increase.
- In terms of Brake Thermal Efficiency (BTE), diesel achieves 25.3%, but PNO10 experiences a 5.9% decrease, PNO20 drops by 12.7%, and PNO30 shows a 19.8% reduction.
- Carbon monoxide (CO) emissions rise markedly with higher pine oil blends, increasing by 15.4% for PNO10, 21.2% for PNO20, and 26.9% for PNO30 compared to diesel's 0.52%. Hydrocarbon (HC) emissions also follow a similar pattern, increasing by 7.9%, 11.1%, and 15.9% for PNO10, PNO20, and PNO30, respectively, compared to diesel's 63 ppm. Smoke density also increases, with PNO10 showing a 2.3% rise, PNO20 a 6.8% rise, and PNO30 an 11.4% rise compared to diesel's 43 HSU.
- In contrast, nitrogen oxide (NOx) emissions decrease as pine oil concentration rises. Compared to diesel's 723 ppm, PNO10 has a 5.0% reduction, PNO20 has a 10.6% decrease, and PNO30 shows a 15.2% decline.
- In-cylinder pressure also drops with higher pine oil content, decreasing by 2.8% for PNO10, 4.2% for PNO20, and 5.6% for PNO30 compared to diesel's 71 bar. Similarly, the Heat Release Rate (HRR) reduces with increasing pine oil, with PNO10 showing a 3.4% decrease, PNO20 a 6.9% drop, and PNO30 an 8.6% decline compared to diesel's 58 kJ/m^3deg.

Overall, increasing the concentration of pine oil in the blend leads to higher BSFC, CO, HC, and smoke emissions, while BTE, NOx emissions, in-cylinder pressure, and HRR decrease compared to diesel, reflecting distinct differences in performance and emissions.

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