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Original Article

Impact of Pine Oil Blend in CRDI Diesel Engine with Different Injection Pressures

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Abstract - *Concerns about running out of fossil fuels and harming the environment have led to research into alternative fuels. This study examines how pine oil blends work in a CRDI diesel engine with different injection pressures. The goal is to understand the fuel's properties and performance. We looked at the chemical and physical properties of pine oil biodiesel blends. The oil samples were tested using methods like GCMS and FTIR to learn about their chemical makeup and functional groups. We also analyzed how the oil behaves at different temperatures. Nanoparticles added to the fuel were studied with SEM to see their size and shape. These tests gave us important information about the quality and suitability of pine oil biodiesel blends for diesel engines. The study also evaluates how well pine oil biodiesel blends perform and their emissions in a CRDI diesel engine under different conditions. First, the engine was tested with blends at different load levels (10%, 20%, and 30%) to find the best blend ratio. The 20% pine oil biodiesel blend was found to be the best. Then, the injection pressure was changed from 400 to 1000 bar to find the best pressure for engine performance and reducing emissions. The best pressure was 800 bar. We also added Nano* TiO_2 *(50 & 75 ppm) with ethanol (5% & 10%) to the fuel blend, which improved combustion efficiency and reduced harmful emissions. The results showed that pine oil blends when optimized with the right injection pressures and additives, can greatly improve engine performance and reduce emissions compared to regular diesel. These findings suggest that pine oil biodiesel blends, especially with nanoparticles and ethanol, are a good and eco-friendly alternative to conventional diesel fuel. This study offers practical solutions for sustainable energy and reducing environmental impact.*

Keywords - *Pine oil blend, CRDI, GC-MS, FTIR, TGA, Injection pressure.*

1. Introduction

The world is facing a critical issue with the depletion of fossil fuels and the increase in environmental pollution. To address these problems, there is a growing interest in finding alternative and renewable energy sources. Biodiesel is a type of renewable fuel that can be made from various biological sources like vegetable oils and animal fats. It is considered a cleaner alternative to conventional diesel because it produces fewer pollutants and is biodegradable. Pine oil, which is derived from pine trees, is one of the promising sources of biodiesel. It contains high levels of oxygen, which helps in better combustion. This study focuses on the use of pine oil biodiesel in Common Rail Direct Injection (CRDI) diesel engines. These engines are known for their high efficiency and lower emissions compared to traditional diesel engines. Previous research has shown that biodiesel can significantly reduce greenhouse gas emissions and improve engine performance. For example, Gumus (2008) evaluated hazelnut kernel oil as an alternative fuel for diesel engines and found it to be a viable option due to its favorable properties [1]. Similarly, Kumar et al. (2006) explored ethanol animal fat emulsions and highlighted the benefits of biodiesel blends in improving engine performance and reducing emissions [2]. Further research by Saravanan et al. (2020) demonstrated the positive impact of dual biodiesel blends of Rapeseed and Mahua on engine performance [3].

This research contributes to the field of alternative fuels by providing detailed insights into the use of pine oil biodiesel in CRDI diesel engines. By optimizing fuel blends and injection pressures, the study aims to enhance engine performance and reduce harmful emissions. The findings can help develop guidelines for using pine oil biodiesel and promote greener and more sustainable fuel options for the future. Alagu et al. (2019) demonstrated the potential of novel biodiesels, such as water hyacinth biodiesel, in existing diesel engines, showing significant improvements in performance and emission characteristics [4]. This study aims to achieve similar breakthroughs with pine oil biodiesel blends. Additionally, research by Bhowmik et al. (2018) using artificial intelligence to predict diesel engine performance with biodiesel blends underscores the importance of innovative approaches in optimizing biodiesel use [6]. The study focuses on the use of pine oil blends in CRDI diesel engines, examining their performance and emissions at various injection pressures under controlled experimental conditions. While these conditions provide valuable insights, they may not fully replicate real-world driving scenarios. Additionally, the study primarily investigates the impact of Nano TiO_2 and ethanol additives, leaving the exploration of other potential additives for future research.

2. Literature Review

The search for alternative fuels has become more intense due to environmental concerns and the limited supply of fossil fuels. Biodiesel, produced from renewable resources, is one of the most promising alternatives. It is biodegradable, non-toxic, and can significantly reduce emissions of carbon dioxide (CO_2), nitrogen oxides (NOx), and particulate matter compared to traditional diesel. Pine oil, derived from pine trees, is a renewable resource with a high oxygen content, making it an excellent candidate for biodiesel. It improves combustion efficiency and reduces emissions, as demonstrated in studies by Kumar et al. (2006) and Saravanan et al. (2020) [2, 3].

The chemical and physical properties of pine oil make it suitable for biodiesel production. Its high oxygen content enhances combustion efficiency, while its chemical composition ensures compatibility with diesel engines. Gumus (2008) highlighted the favorable properties of hazelnut kernel oil, which shares similarities with pine oil in terms of renewable source characteristics [1]. Previous studies have shown that biodiesel blends can improve engine performance and reduce emissions. For example, Kumar et al. (2006) explored ethanol animal fat emulsions and demonstrated significant benefits [2]. Saravanan et al. (2020) and Alagu et al. (2019) also highlighted the positive impact of various biodiesel blends on engine performance and emissions [3, 4].

Common Rail Direct Injection (CRDI) diesel engines use advanced technology to deliver precise amounts of fuel into the combustion chamber at high pressures, resulting in better fuel atomization, improved combustion efficiency, and lower emissions. These engines are particularly suitable for biodiesel blends due to their ability to handle different fuel types and compositions. CRDI engines utilize a high-pressure fuel rail to deliver fuel directly into the combustion chamber. The fuel injection is controlled by an Electronic Control Unit (ECU) that adjusts the timing and amount of fuel injected based on engine load and speed, ensuring optimal combustion. The injection pressure in CRDI engines significantly impacts engine performance and emissions. Higher injection pressures lead to better fuel atomization and more complete combustion. Studies by Panithasan et al. (2019) and Vallinayagam et al. (2018) demonstrated the benefits of high-pressure injection systems in improving engine efficiency and reducing emissions [5, 8].

The injection pressure plays a crucial role in the performance and emissions of diesel engines. Higher injection pressures result in better fuel atomization, more complete combustion, and lower emissions. Panithasan et al. (2019) studied the impact of rice husk nanoparticles on the performance and emission aspects of a diesel engine running on blends of pine oil-diesel, demonstrating the importance of optimizing injection pressures [5].

The combustion characteristics of biodiesel blends, including ignition delay, combustion duration, and peak pressure, are influenced by the injection pressure. Higher pressures generally lead to more efficient combustion, as shown in studies by Saravanan et al. (2020) and Bhowmik et al. (2018) [3, 6]. Biodiesel blends can significantly reduce emissions of CO_2, NOx, and particulate matter. Studies by Kumar et al. (2006) and Khan et al. (2019) highlighted the emission reduction benefits of biodiesel blends [2, 7].

The performance metrics of diesel engines, including Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), and engine power output, are influenced by the type of fuel used. Studies have shown that biodiesel blends can improve these metrics. For example, Alagu et al. (2019) demonstrated the performance benefits of water hyacinth biodiesel blends in diesel engines [4].

3. Materials and Method

3.1. Research Design

This chapter details the research design and methodology employed to investigate the impact of pine oil biodiesel blends in a Common Rail Direct Injection (CRDI) diesel engine under varying injection pressures. The study is structured to provide a comprehensive analysis of fuel properties, engine performance, and emission characteristics, ensuring that the findings are robust and applicable. The methodology involves preparing the biodiesel, setting up the engine for testing, and conducting a series of experiments under controlled conditions to measure and analyze various performance and emission parameters.

3.2. Description of the Engine Test Setup

Experiments were carried out using a Kirloskar AV1 engine, a four-stroke, single-cylinder, air-cooled diesel engine with a Common Rail Direct Injection (CRDI) system. The layout of the experimental setup is shown in Figure 1. The engine, which has a rated power output of 5.2 kW, was run at a steady speed of 1500 rpm and an injection pressure of 220 bar. The engine specifications are detailed in Table 1. The fuel flow rate was determined using a burette and a stopwatch. Exhaust gas temperature was measured with a thermocouple connected to a digital display. Smoke density was assessed using a Hartridge smoke meter, while emissions of NOx, HC, and CO were measured with an AVL five-gas analyzer.

Table 1. Test engine specifications

Type	Single Cylinder, Vertical, Water Cooled, 4Stroke VCR Diesel Engine
Bore	80mm
Stroke	110mm
Compression Ratio	17.5:1
Orifice Diameter	20mm
Dynamometer Arm Length	195mm
Maximum Power	3.7kW
Speed	1500rpm
Loading Device	Eddy Current Dynamometer
Mode of Starting	Manually Cranking
Injection Timing	23°C before TDC

Cylinder pressure data was gathered using a Legion Brothers combustion analyzer. Different fuel blends were tested at a constant engine speed of 1500 rpm under various load conditions. Key parameters such as engine speed, fuel flow, and emission levels (NOx, HC, CO, and smoke) were recorded.

Engine performance was assessed by evaluating brake thermal efficiency, brake power, and specific fuel consumption. Additionally, combustion characteristics, including cylinder pressure and heat release rate, were measured for each fuel blend.

3.3. Fuel Preparation

The preparation of biodiesel from pine oil involves several critical steps. First, the pine oil is converted into biodiesel through the transesterification process. This chemical reaction involves reacting pine oil with methanol in the presence of a catalyst, typically sodium hydroxide or potassium hydroxide.

The process produces methyl esters (biodiesel) and glycerol as a byproduct. The reaction mixture is heated and stirred for a specific duration to ensure complete conversion of the oil into biodiesel. After the reaction, the crude biodiesel is washed with warm water to remove any residual catalyst, soap, and other impurities. The washed biodiesel is then dried to eliminate any remaining water content, resulting in pure biodiesel.

For this study, Nano TiO_2 and ethanol are added to the biodiesel in concentrations of 50 ppm and 75 ppm for Nano TiO_2 and 5% and 10% for ethanol, respectively. These additives are chosen for their potential to enhance fuel properties, improve combustion efficiency, and reduce emissions.

3.4. Experimental Procedure

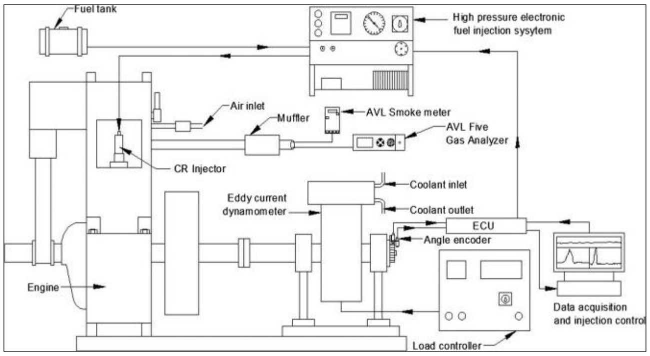

Fig. 1 Experimental setup

The experimental procedure involves several steps. Initially, the engine performance and emission characteristics are measured using standard diesel fuel to establish a baseline. Following this, the engine is tested with various blends of pine oil biodiesel (10%, 20%, and 30%) under different load conditions, such as 10%, 50%, 75%, and 100% of full load. The injection pressure varies from 400 bar to 1000 bar in increments, such as 400 bar, 600 bar, 800 bar, and 1000 bar, to determine the optimal pressure for maximizing engine performance and minimizing emissions.

During the tests, key performance parameters such as Brake Thermal Efficiency (BTE), Brake Specific Fuel Consumption (BSFC), and power output are recorded. Emission parameters, including carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HC), and Particulate Matter (PM) are measured using sophisticated emission analyzers. The collected data is then analyzed to identify the optimal blend ratio and injection pressure, focusing on achieving the best balance between high performance and low emissions.

4. Chemical Properties and Analysis

4.1. FITR Analysis of Pine Oil

The Fourier Transform Infrared (FTIR) analysis of pine oil biodiesel provides important insights into its chemical makeup and how it can be used as fuel. The FTIR spectrum shows in Figure 2 different peaks that identify various chemical groups present in the biodiesel. These groups are crucial for understanding how biodiesel will perform when used in engines.

The analysis shows the presence of hydrocarbons, which are essential components of fuel. These hydrocarbons determine how much energy the biodiesel contains and how it will burn. There is a significant peak around 1741.61 cm-1, indicating the presence of carbonyl groups. This is a characteristic feature of esters, which are created during the process of converting pine oil into biodiesel.

A broad peak near 3400 cm-1 suggests the presence of O-H groups, which could come from moisture or unreacted alcohols used in making the biodiesel. Peaks around 2929.82 cm-1 and 2854.71 cm-1 show C-H stretching vibrations, confirming the presence of aliphatic hydrocarbons. These hydrocarbons have long carbon chains typical of biodiesel. Other peaks at 1458.23 cm-1 and 1377.38 cm-1 are due to C-H bending vibrations, which further indicate the presence of methyl and methylene groups in the biodiesel.

Overall, the FTIR analysis shows that pine oil biodiesel has the necessary chemical properties similar to conventional biodiesel, making it a good alternative fuel. The presence of esters and hydrocarbons ensures that it will burn well in diesel engines. This analysis confirms that pine oil can be successfully converted into biodiesel, which is a renewable and cleaner-burning alternative to fossil diesel.

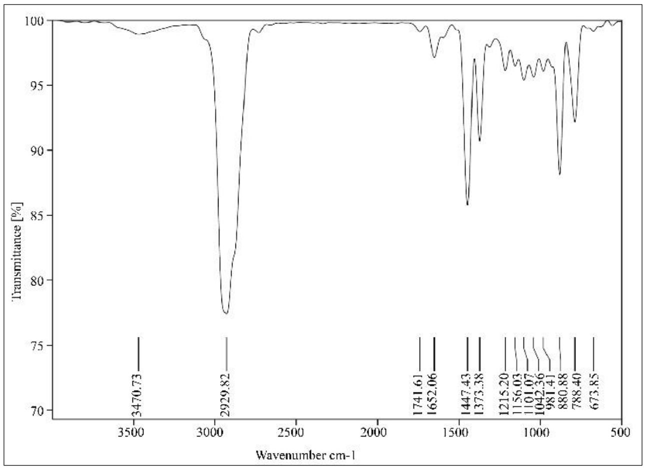

Fig. 2 FTIR analysis of pine oil

4.2. GC-MS Analysis of Pine Oil

The Gas Chromatography-Mass Spectrometry (GC-MS) analysis of pine oil biodiesel identifies various chemicals present in the fuel, helping us understand its performance as a fuel. The analysis detected several important compounds, as shown in Figure 3, including 2,3-Dichloropropionitrile, which appeared at 13.618 minutes and again at 17.514 minutes with a molecular weight of 123. Another significant compound is 3-Ethyl-benzotriazin-4-one, found at 12.104 minutes with a molecular weight of 175.

Benzonitrile, N-oxide was observed at 15.680 minutes with a molecular weight of 119. Nitroethene, 2-(2,4-dibenzyloxy) phenyl-, appeared multiple times, showing up consistently with a molecular weight of 361. Dimethyldithiocarbamic Acid, S-(2-cyano-2-methyl-1-phenyl) vinyl Ester was detected at 17.052 minutes with a molecular weight of 262, and Benzaldehyde, 4-(1-phenyl-2-propenyloxy) was also found at 17.514 minutes with a molecular weight of 238.

Benzene methanol, 2-nitro was present at 22.036 minutes with a molecular weight of 153 and 1,1-Cyclopropanedicarbonitrile, 2-ethyl-2-methyl- was found at 22.645 minutes with a molecular weight of 134. Additionally, 7-Methylbicyclo [4.4.1] undeca-2,4,8-triene was identified at 23.445 minutes with a molecular weight of 160, and Bicyclo [3.3.1] non-6-ene-3-carboxylic acid was detected at 21.558 minutes with a molecular weight of 166.

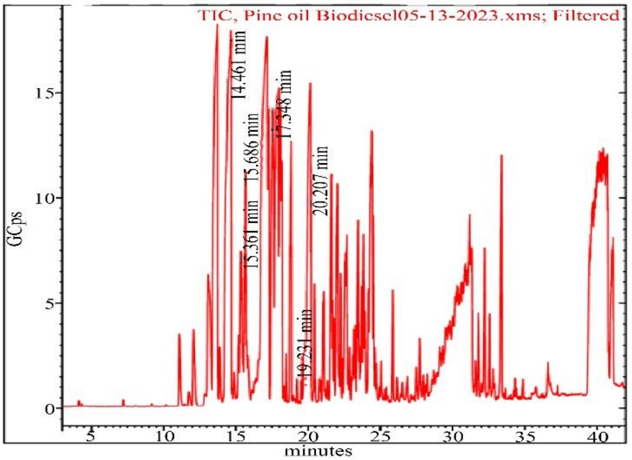

Fig. 3 GC-MS analysis of pine oil

The analysis also found Bis(dimethylthiocarbamyl) sulfide at 18.808 minutes with a molecular weight of 208, 2-Cyclopropylbenzoic Acid at 25.847 minutes with a molecular weight of 162, and 8-Methylene-3-oxatricyclo [5.2.0.0(2,4)] nonane at 27.714 minutes with a molecular weight of 136. Other compounds include 1-[1-(2,2-Dichlorovinylimino)-2,2-dimethylpropyl]-3-(p-tolyl) thiourea found at 34.888 minutes with a molecular weight of 343, Serotonin detected at 36.604 minutes with a molecular weight of 176, 3-Cyclopentylpropionic Acid, 2-tetrahydrofurylmethyl Ester found at 41.007 minutes with a molecular weight of 226, 2,3-Dihydroindole-4-ol-2-one, 5,7-dibromo-3,3-dimethyl- identified at 31.177 minutes with a molecular weight of 333, 3-(Phthalimido methyl) benzoic Acid detected at 33.374 minutes with a molecular weight of 281, and 2,4-Bis(diazo)adamantane found at 32.540 minutes with a molecular weight of 188. The GC-MS analysis shows that pine oil biodiesel contains a mix of different chemicals, each with distinct molecular weights and detection times. This complicated chemical constitution helps us understand biodiesel's behavior as a fuel, implying that it has the necessary properties to perform effectively in diesel engines and is a viable alternative to traditional fossil fuels.

4.3. TGA of Pine Oil

The Thermogravimetric Analysis (TGA) of pine oil biodiesel provides useful information about how it behaves when heated, as shown in Figure 4. During the analysis, the biodiesel sample was heated from 30°C to 1000°C at a rate of 10°C per minute in a nitrogen atmosphere, and the changes in its weight were recorded. The initial weight of the biodiesel sample was 7.5710 mg. The analysis showed two main stages of weight loss. The first significant weight loss happened between 39.833°C and 118.500°C, where the sample lost about 97.75% of its initial weight, which is around 7.4010 mg.

This indicates that many of the volatile compounds in the biodiesel evaporated during this stage. The second stage of weight loss occurred between 118.500°C and 138.167°C, where the sample lost an additional 2.96% of its weight, which is approximately 0.2240 mg. This suggests that the more stable components of the biodiesel decomposed during this stage. The TGA curve shows that pine oil biodiesel loses most of its weight at lower temperatures due to the evaporation of volatile compounds.

This is typical behavior for biodiesel, which contains various organic compounds that evaporate easily. The remaining weight loss at higher temperatures is due to the decomposition of more stable components. The TGA analysis of pine oil biodiesel indicates that it has a high content of volatile compounds that evaporate at lower temperatures and a smaller number of stable components that break down at higher temperatures. This information is critical for knowing how biodiesel will operate when used as a fuel.

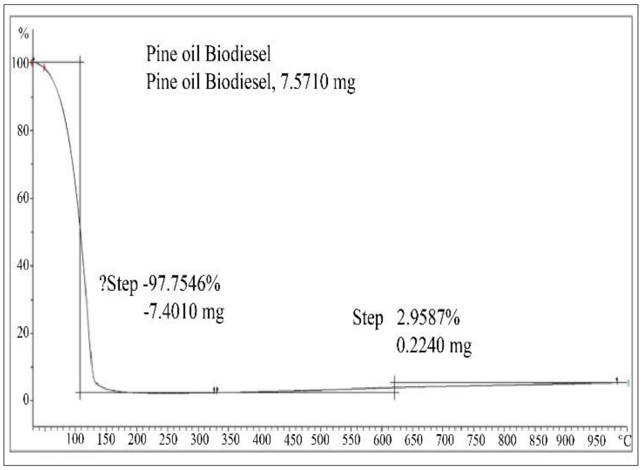

Fig. 4 TGA analysis of pine oil

5. Results and Discussion

5.1. Engine Performance

5.1.1. Brake Specific Fuel Consumption (BSFC)

Brake Specific Fuel Consumption (BSFC) is a critical measure in assessing the efficiency with which an engine utilizes fuel to produce power. In the context of varying injection pressures and using the PNO20 blend, there is a notable trend where the BSFC reduces as the pressure increases from 400 bar to 1000 bar, as shown in Figure 5. Initially, at 400 bar, the engine exhibits high BSFC values, suggesting poor fuel efficiency. This inefficiency is largely because at lower pressures, the fuel atomization and air-fuel mixing are not optimal, leading to incomplete combustion. As the pressure is ramped up to 600 bar and then to 800 bar, the BSFC progressively lowers, indicating an improvement in how efficiently the engine utilizes the fuel.

This improvement is attributed to better atomization and mixing of the fuel at higher pressures, which facilitates more complete combustion. By the time the pressure reaches 1000 bar, the BSFC for the PNO20 blend closely aligns with that of conventional diesel, signifying that the blend is nearly as efficient as diesel in terms of fuel consumption at this high pressure. This outcome suggests that biodiesel blends like PNO20 can achieve optimal performance and compete closely with diesel under suitable operating conditions (Jung et al., 2005).

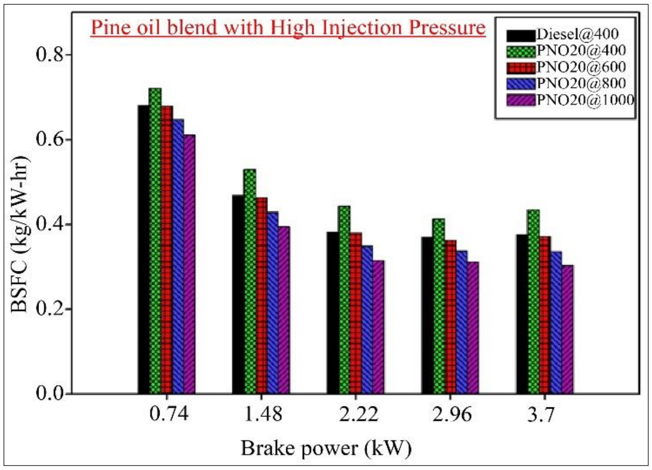

Fig. 5 BSFC against BP

5.1.2. Brake Thermal Efficiency (BTE)

Brake Thermal Efficiency (BTE) measures the efficiency with which an engine converts the heat from fuel combustion into mechanical work. This metric is pivotal for understanding overall engine performance and efficiency. Observations from the experiment shown in Figure 6 that as injection pressure increases, so does the BTE for both diesel and the PNO20 blend.

This increase in efficiency with higher pressures is due to enhanced fuel atomization and a better mix between air and fuel, which promotes more complete combustion. At lower pressures, such as 400 bar, the BTE is comparatively lower for PNO20 than for diesel, which could be attributed to the inherent properties of biodiesel, including higher viscosity and different combustion characteristics. However, as the injection pressure is increased to 600, 800, and finally 1000 bar, the BTE of PNO20 gradually improves and approaches that of diesel. By the time the pressure reaches 1000 bar, the efficiency gap between PNO20 and diesel narrows significantly, indicating that high injection pressures can mitigate the typical performance shortfalls of biodiesel, making it a more viable and efficient fuel option (Fangsuwannarak & Triratanasirichai, 2013).

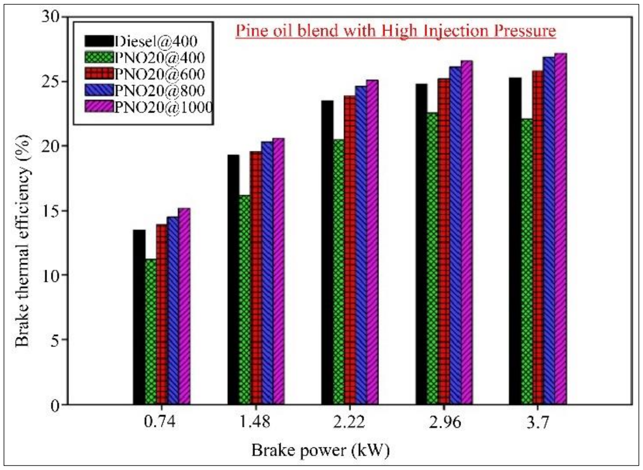

Fig. 6 BTE against BP

5.2. Emission Parameters

5.2.1. Carbon Monoxide (CO) Emissions

Carbon monoxide (CO) emissions are a direct indicator of the completeness of combustion within an engine, with high levels indicating incomplete combustion, as shown in Figure 7. In the tests conducted, it was found that at 400 bar, both diesel and PNO20 exhibit relatively high CO emissions. However, as the injection pressure is increased, there is a steady decline in these emissions for PNO20. This reduction is most notable when the pressure reaches 1000 bar, where the CO emissions are significantly lower and approach those of diesel.

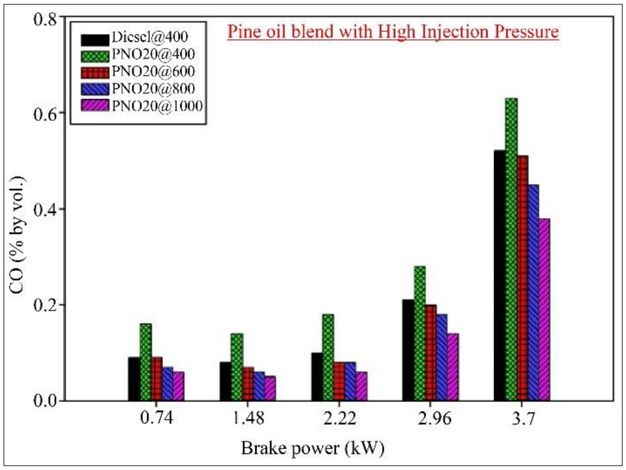

Fig. 7 CO emissions against BP

The decrease in CO emissions with increased pressure is attributable to the improved atomization of the fuel and better mixing with air, which facilitates more complete combustion of the fuel particles. This trend underscores the potential environmental benefits of operating biodiesel blends like PNO20 at higher injection pressures, as it leads to cleaner combustion and lower emissions of harmful gases like carbon monoxide (Qi et al., 2010).

5.2.2. Hydrocarbon (HC) Emissions

Hydrocarbon (HC) emissions, which result from unburned fuel, provide insights into the combustion efficiency of the engine. The analysis shown in Figure 8 reveals that at a lower injection pressure of 400 bar, HC emissions are considerably higher for the PNO20 blend compared to diesel.

This suggests that at lower pressures, the combustion of the biodiesel blend is less complete, possibly due to less effective fuel atomization and mixing. However, as the injection pressure increases to 600, 800, and finally, 1000 bar, there is a progressive decrease in HC emissions. This reduction indicates that higher pressures improve the combustion process, leading to more complete burning of the fuel and, consequently, fewer emissions of unburned hydrocarbons. By optimizing injection pressures, it is possible to enhance the environmental performance of biodiesel blends by minimizing HC emissions, which are a significant contributor to air pollution (Kao et al., 2008).

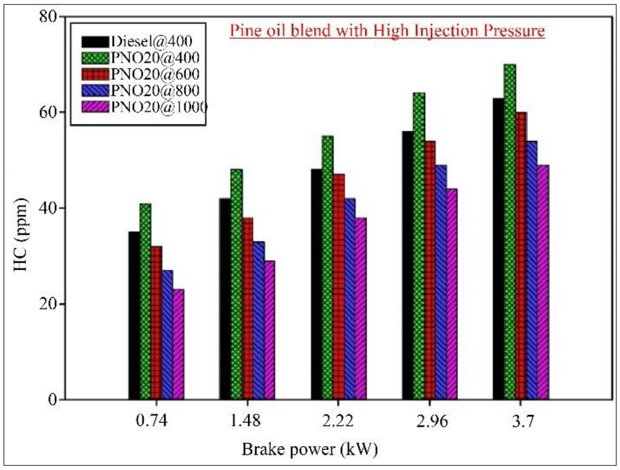

Fig. 8 HC emissions against BP

5.2.3. Oxides of Nitrogen (NOx) Emissions

Nitrogen oxide (NOx) emissions are particularly critical pollutants emitted from combustion engines, formed when nitrogen in the air reacts with oxygen under high temperature and pressure conditions inside the engine cylinder, as shown in Figure 9. Unlike other emissions, NOx levels typically increase with higher injection pressures due to the increased combustion temperatures involved.

During the experiments, at a lower pressure of 400 bar, the NOx emissions for both diesel and the PNO20 blend were comparatively lower, with diesel producing slightly more NOx than the biodiesel blend. As the injection pressure increased to 600 bar and further to 800 bar, the NOx emissions from PNO20 also increased, surpassing those from diesel at the same conditions. By the time the pressure reached 1000 bar, the NOx emissions for PNO20 peaked at approximately 880 ppm.

This rise in NOx emissions at higher pressures is attributed to the higher temperatures reached during more efficient combustion processes. The data illustrates a clear trade-off in emission control strategies-while higher pressures can reduce emissions like CO and HC by enhancing combustion efficiency, they can conversely increase NOx emissions, thus presenting challenges in meeting environmental standards without additional NOx mitigation strategies (Selvaganapthy et al., 2013).

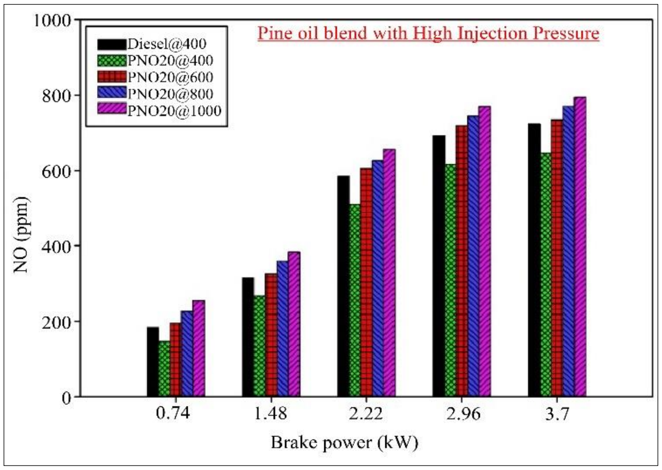

Fig. 9 NOx emissions against BP

5.2.4. Smoke Density Emissions

Smoke density is a measure of the particulate matter emitted by an engine, which can have significant environmental and health impacts. Figure 10 indicates that at the initial 400 bar pressure, smoke emissions for the PNO20 blend are higher than those for diesel, reflecting less efficient combustion. As the injection pressure is increased, there is a noticeable reduction in smoke emissions.

At 600 bar, emissions decrease slightly, and this downward trend continues more sharply at 800 and 1000 bar. The substantial reduction in smoke emissions at higher pressures can be attributed to improved atomization of the fuel and better mixing with air, which enhances the completeness of the combustion process.

This results in fewer particulates being released into the atmosphere, thus reducing the environmental impact of the emissions. The findings suggest that operating biodiesel blends like PNO20 at higher injection pressures not only improves engine performance but also contributes to cleaner exhaust and reduced particulate emissions (Jung et al., 2005).

5.3. Combustion Characteristics

5.3.1. Heat Release Rate (HRR)

The Heat Release Rate (HRR) is an important measure for assessing the combustion efficiency of an engine. It describes the rate at which fuel energy is converted into heat during combustion, directly impacting engine performance and emissions.

In Figure 11, the PNO20 blend at 400 bar, the HRR peaks at about 50 kJ/m³-deg, slightly lower than that of diesel, which reaches around 56 kJ/m³-deg at the same pressure. This lower HRR at lower pressures indicates less efficient combustion, likely due to poorer fuel atomization and mixing. However, as the injection pressure is increased to 600 bar, the HRR for PNO20 increases to about 58 kJ/m³-deg, suggesting an improvement in combustion efficiency.

This trend continues at 800 bar, with the HRR further increasing to approximately 63 kJ/m³-deg. At the highest tested pressure of 1000 bar, the PNO20 blend exhibits its highest HRR at around 66 kJ/m³-deg. These observations reflect that higher injection pressures significantly enhance the combustion process, leading to more complete and efficient burning of the fuel.

The increase in HRR with pressure is consistent with better fuel atomization, which allows for more effective mixing with air and, thus, more complete combustion, ultimately translating into improved engine performance and lower emissions of incomplete combustion products (Fangsuwannarak & Triratanasirichai, 2013).

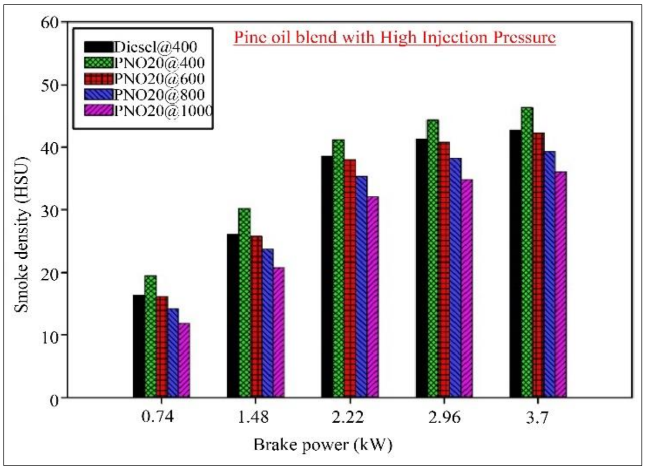

Fig. 10 Smoke density emissions against BP

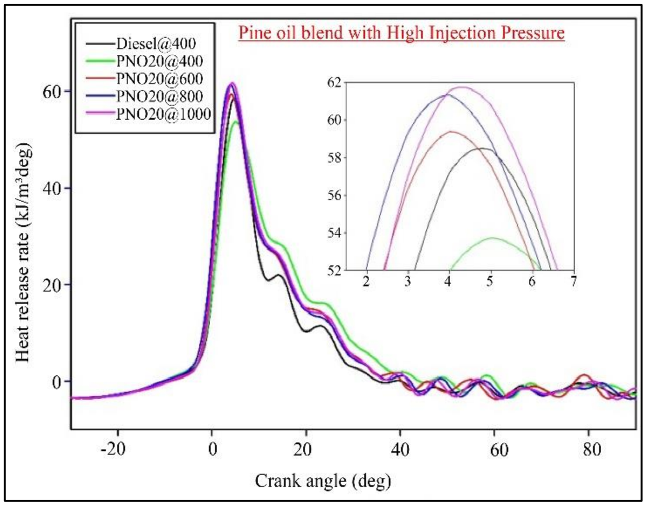

Fig. 11 HRR against the Crank angle

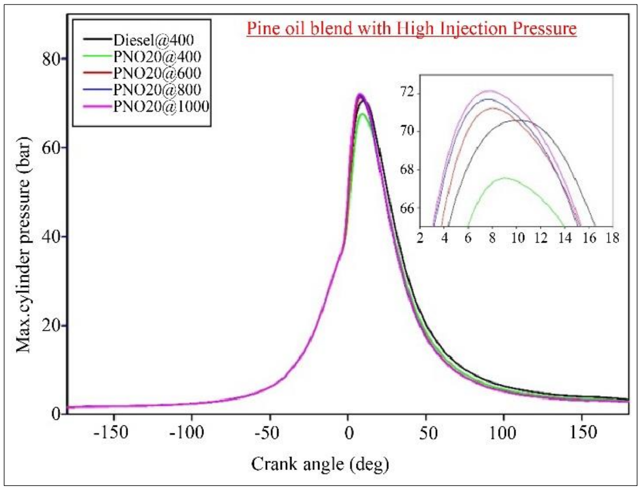

Fig. 12 Cylinder pressure against Crank angle

5.3.2. In-Cylinder Pressure

In-cylinder pressure is a fundamental parameter in understanding the dynamics of the combustion process within an engine. Higher in-cylinder pressures generally indicate a more vigorous combustion process, leading to better engine performance, as shown in Figure 12. In the experiment, at the lowest injection pressure of 400 bar, the PNO20 blend exhibited a peak in-cylinder pressure of about 68 bar, slightly lower than that of diesel at the same pressure, which peaked at around 70 bar.

This lower peak pressure for PNO20 can be attributed to the fuel's lower calorific value and different physical properties compared to diesel. As the injection pressure was incrementally raised to 600 bar, the peak pressure for PNO20 increased to approximately 72 bar, reflecting improved combustion efficiency due to enhanced fuel atomization and mixing. At 800 bar and then at 1000 bar, the peak pressures continued to rise, reaching around 74 bar and 76 bar, respectively.

These increases underscore that higher injection pressures can significantly enhance the combustion process by promoting better atomization and more complete burning of the fuel. The measurements at higher pressures also show a delay in reaching the peak pressure at lower pressures, but as the pressure increases, the peak pressure timing aligns more closely with the Top Dead Center (TDC), indicating a more efficient combustion cycle (Jung et al., 2005).

6. Conclusion

The performance, emissions, and combustion characteristics of a CRDI diesel engine using a 20% pine oil biodiesel blend (PNO20) were tested at different injection pressures: 400 bar, 600 bar, 800 bar, and 1000 bar. Based on the investigation, the following conclusions are drawn:

- ❖ The Brake Specific Fuel Consumption (BSFC) is higher for PNO20 at 400 bars compared to regular diesel at all load levels. However, as the injection pressure increases to 600, 800, and 1000 bar, the BSFC decreases, indicating that the engine uses fuel more efficiently at higher pressures.
- ❖ The Brake Thermal Efficiency (BTE) of regular diesel is higher than PNO20 at 400 bars across all loads. However, as the injection pressure rises, the BTE for PNO20 improves, with the highest efficiency observed at 1000 bar due to better fuel-air mixing and combustion.
- ❖ CO emissions decrease as the injection pressure increases for PNO20. At 1000 bars, CO emissions are significantly lower than at 400 bars, indicating more complete combustion and efficient conversion of carbon monoxide to carbon dioxide.
- ❖ HC emissions are higher for PNO20 at 400 bars compared to regular diesel. However, as the injection pressure rises, HC emissions decrease, with the lowest emissions recorded at 1000 bar, suggesting better combustion efficiency.
- ❖ NOx emissions are lower for regular diesel compared to PNO20 at all injection pressures. NOx emissions increase with higher injection pressures for PNO20, with the highest levels observed at 1000 bar due to higher combustion temperatures.
- ❖ Smoke emissions are higher for PNO20 at 400 bars compared to regular diesel. However, smoke density decreases as the injection pressure increases, with the lowest levels noted at 1000 bar, indicating cleaner combustion and reduced particulate emissions.
- ❖ Higher injection pressures for PNO20 result in an increased Heat Release Rate (HRR). The maximum HRR is seen at 1000 bar, indicating more efficient combustion and improved fuel-air mixing. Higher pressures produce a higher peak pressure and better combustion characteristics.

In summary, raising injection pressure in a CRDI diesel engine fueled by PNO20 improves engine efficiency and lowers emissions, with the exception of NOx, which increases at higher pressures. Higher injection pressures improve fuel atomization and combustion efficiency, leading to lower BSFC, higher BTE, and lower CO, HC, and smoke emissions. However, the rise in NOx emissions at greater pressures implies that additional methods are required to reduce this effect. Future research should concentrate on creating innovative injection techniques, such as numerous injection events, to improve the performance and emissions of biodiesel mixes in diesel engines.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper. The first author, C Manikandan, is the sole author of this research, and C. Syed Aalam has been added as a co-author due to their role as the project guide, with no influence from any secondary interests.

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