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Original Article

Analysis of Performance, Emissions, and Combustion in a CRDI Diesel Engine Operating on Soapnut Oil as Fuel

Manikandan Chandrasekaran[1], C. Syed Aalam[2], S. Devi[3], K. Manikandan[2]

[1,2]*Department of Mechanical Engineering, FEAT, Annamalai University, Tamilnadu, India.*
[3]*Department of Civil Engineering, FEAT, Annamalai University, Tamilnadu, India.*

Corresponding Author : cpmanikandan07@gmail.com

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Abstract - *This study explores the performance of a Common Rail Direct Injection (CRDI) diesel engine using soapnut oil blends as an alternative fuel. In light of growing environmental concerns and the depletion of fossil fuel reserves, the need for sustainable fuel solutions has become more urgent. Soapnut oil, derived from Sapindus mukorossi seeds, emerges as a promising biodiesel candidate. This research examines how soapnut oil blends affect key engine performance parameters, including brake-specific fuel consumption, thermal efficiency, and exhaust emissions such as carbon monoxide, nitrogen oxides, and smoke. Additionally, in-depth combustion analysis is conducted, utilizing in-cylinder pressure measurement and heat release rate analysis better to understand the combustion characteristics of soapnut oil blends. The results of this study provide valuable insights into the feasibility, benefits, and challenges of using soapnut oil as an alternative fuel in CRDI diesel engines, contributing to sustainable energy strategies in the transportation sector.*

Keywords - *Common rail direct injection, Diesel engine, Soapnut oil, Combustion, Emission.*

1. Introduction

The global energy crisis and environmental concerns have sparked significant interest in renewable and sustainable fuel sources. Biodiesel, derived from various non-edible oils, is a promising alternative due to its renewable nature, biodegradability, and reduced environmental impact compared to conventional fossil fuels [1]. Among the various feedstocks suitable for biodiesel production, soapnut oil (extracted from *Sapindus mukorossi*) stands out due to its high oil yield, non-edible nature, and availability in tropical regions [2]. With a rich fatty acid profile, soapnut oil is well-suited for biodiesel production through transesterification, a process that converts the oil into methyl esters, commonly known as biodiesel [3]. Its potential as a biodiesel feedstock has been underscored by its ability to produce lower emissions while maintaining comparable engine performance [4]. Common Rail Direct Injection (CRDI) diesel engines are preferred for testing soapnut oil biodiesel because they can precisely control fuel injection parameters such as pressure, timing, and duration. These engines are known for better fuel atomization and efficient combustion, making them ideal for evaluating the performance of alternative fuels like biodiesel [5]. Studies have shown that using soapnut oil biodiesel in CRDI engines can enhance Brake Thermal Efficiency (BTE), indicating the engine’s effectiveness in converting fuel energy into mechanical power [6]. This improvement is mainly due to the better combustion characteristics of soapnut oil biodiesel, facilitated by its oxygen content, which supports more complete combustion [7]. Brake-specific fuel consumption (BSFC), which measures the fuel consumption rate relative to power output, also improves when soapnut oil biodiesel blends are used in CRDI engines. Adjusting injection parameters, such as increasing injection pressure, has been found to reduce BSFC, thus improving overall fuel efficiency [8]. Research suggests that varying the blend ratios of soapnut oil biodiesel with conventional diesel can help strike an optimal balance between performance and fuel economy [9]. When it comes to emissions, soapnut oil biodiesel blends show a significant reduction in harmful pollutants such as carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter (PM) compared to conventional diesel [10]. This reduction is largely due to the oxygen in soapnut oil biodiesel, leading to more complete combustion and fewer incomplete combustion byproducts [11]. However, one challenge with using biodiesel in CRDI engines is the potential increase in nitrogen oxide (NOx) emissions. This increase is mainly due to the higher combustion temperatures resulting from biodiesel’s oxygenated nature, which promotes NOx formation. As a result, optimizing injection parameters becomes essential to control NOx emissions effectively [12]. The combustion characteristics of soapnut oil biodiesel include a shorter ignition delay and the interval between the start of fuel injection and the onset of combustion. This shorter delay helps in reducing the accumulation of unburned fuel, contributing to a smoother and more efficient combustion process [13]. Additionally, soapnut oil biodiesel generally produces higher peak cylinder pressure and faster heat release rates than diesel due to its rapid combustion and oxygen-rich composition [14]. The oxygen in the fuel aids in better combustion, leading to more complete burning and efficient energy release [15]. The performance of CRDI engines with soapnut oil biodiesel can be further enhanced through optimization techniques like Response Surface Methodology (RSM) and Genetic Algorithm (GA).

These methods determine the best operating parameters, such as injection pressure, timing, and blend ratio, to maximize engine performance and minimize emissions [16, 17]. RSM has proven effective in identifying optimal conditions for running CRDI engines on soapnut oil biodiesel blends, while GA has helped optimize multiple variables simultaneously, resulting in improved engine performance [18]. Overall, the findings from various studies support the potential of soapnut oil biodiesel as a viable renewable energy source that aligns with global sustainability goals. Its use in CRDI diesel engines offers a feasible alternative to conventional diesel and contributes to reducing greenhouse gas emissions and enhancing energy security [19]. Moving forward, research will focus on addressing NOx emissions and optimizing fuel blends to ensure the practical application of soapnut oil biodiesel in modern diesel engines [20].

2. Literature Review

The urgent shift towards renewable energy sources has been fueled by the decline in fossil fuel reserves and increasing environmental concerns. Among various sustainable fuel options, biodiesel—derived from non-edible oils—has gained traction as a viable alternative. It is favored for its renewable nature, biodegradability, and potential to reduce greenhouse gas emissions compared to traditional diesel fuels [21]. Soapnut oil (Sapindus mukorossi), a non-edible oil obtained from tropical regions, has become an attractive feedstock for biodiesel production due to its high oil yield and compatibility with biodiesel conversion processes [22]. The transesterification method, which converts soapnut oil into biodiesel (methyl esters), has shown promising outcomes, making it a feasible substitute for petroleum-based diesel fuels [23]. Its high fatty acid content and emission-reducing properties position soapnut oil as an efficient choice for biodiesel production, particularly in diesel engines [24].

Common Rail Direct Injection (CRDI) diesel engines are known for their precise control over fuel injection parameters, such as timing, pressure, and duration, making them suitable for evaluating alternative fuels like biodiesel [25]. These engines provide better fuel atomization, leading to more efficient combustion when operating on soapnut oil blends [26]. Research indicates that using soapnut oil biodiesel in CRDI engines enhances Brake Thermal Efficiency (BTE), signifying a more effective conversion of fuel energy into mechanical power [27]. This improvement can be attributed to the oxygen content in soapnut oil biodiesel, which facilitates more complete combustion [28]. Similarly, Brake Specific Fuel Consumption (BSFC), which measures the fuel used relative to power output, tends to decrease with soapnut oil biodiesel blends, indicating better fuel efficiency [29]. Optimizing fuel injection parameters, such as increasing injection pressure, has been shown to reduce BSFC further, enhancing the effectiveness of soapnut oil biodiesel [30]. Adjusting the blend ratios of soapnut oil biodiesel with conventional diesel also helps balance performance and fuel economy [31]. Regarding exhaust emissions, soapnut oil biodiesel blends demonstrate a notable reduction in carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter (PM) compared to regular diesel [32].

This is primarily due to the higher oxygen content in soapnut oil biodiesel, which enables more complete combustion and reduces incomplete combustion byproducts [33]. A challenge, however, is the increase in nitrogen oxides (NOx), which is generally caused by higher combustion temperatures [34]. To address this, optimizing injection timing and engine parameters becomes crucial to control NOx emissions while maintaining efficient combustion [35]. The combustion characteristics of soapnut oil biodiesel include a shorter ignition delay, helping prevent fuel accumulation and promoting smoother combustion [36]. Additionally, soapnut oil biodiesel achieves higher peak cylinder pressure and a faster heat release rate due to its oxygenated nature, which supports rapid combustion [37]. The presence of oxygen allows for more efficient burning and improved energy release, making soapnut oil biodiesel a strong alternative fuel for diesel engines [38]. Optimization techniques like Response Surface Methodology (RSM) and Genetic Algorithm (GA) are essential for refining CRDI engine conditions when using soapnut oil biodiesel. These methods help determine the best settings for parameters such as injection pressure, timing, and blend ratios, thereby improving performance while reducing emissions [39, 40]. RSM has been particularly effective in identifying optimal blend conditions, while GA has been beneficial in optimizing multiple factors to enhance performance [41]. Adopting soapnut oil biodiesel in CRDI diesel engines supports global sustainability efforts and offers a practical, eco-friendly alternative to petroleum-based fuels. Continued research is needed to address remaining challenges, such as NOx emissions and fuel stability, ensuring that soapnut oil biodiesel can be widely utilized in modern diesel engines [42].

3. Materials and Methods

3.1. Production of Soapnut oil

Soapnut oil, extracted from the seeds of Sapindus mukorossi, is a highly promising biofuel feedstock due to its beneficial natural properties and substantial oil yield. The production of this oil utilizes the mechanical extraction process, commonly known as cold pressing, which is both popular and eco-friendly. Figure.1 shows the soapnut oil preparation. This method retains the oil's natural quality, avoiding using chemicals throughout the extraction process. The preparation begins by harvesting ripe soapnut fruits from mature trees. When the fruits are ripe, they turn brown, signaling they are ready for collection. After harvesting, the seeds are separated from the fruit pulp, thoroughly cleaned to remove any residues, and air-dried to ensure they are moisture-free before further processing. Once dried, the seeds are manually cracked to reveal the inner kernels containing a rich oil concentration. The hard shells are removed manually or with simple tools, preparing clean kernels for the pressing stage.

The kernels are then placed into a cold press oil maker, a specialized machine that crushes the kernels without generating excessive heat. The cold pressing technique maintains a controlled temperature, typically below 50°C (122°F), allowing the oil to retain its natural nutrients, aroma, and color. The oil is squeezed out and collected in a container as pressure is applied. At this initial stage, the oil appears yellowish, indicating its crude state. The raw oil often contains small solid particles and other impurities, giving it an unrefined appearance. To refine the oil, it is gently heated in a metal pot over a flame, helping to eliminate moisture and volatile impurities. This moderate heating process purifies the oil and ensures a smoother consistency while preserving its natural properties. After heating, the oil undergoes water separation. It is transferred into a transparent container and left to settle. Because oil and water have different densities, the oil naturally floats to the top, facilitating easy separation. This step ensures the oil is free from residual water, enhancing its stability and extending its shelf life.

Fig. 1 Soapnut oil preparation

Finally, the purified oil is collected into a labeled bottle, which takes on a clear, golden hue, indicating that it is fully refined and ready for use. The resulting soapnut oil retains beneficial properties such as saponins and fatty acids, making it ideal for various uses, including biofuel production, cosmetics, and natural cleaning products. The Mechanical Extraction (Cold Pressing) method maintains the oil's quality and promotes sustainability, making it an effective and environmentally friendly technique for producing high-quality soapnut oil.

3.2. Analysis of the Properties of Soapnut Oil

The thermos-physical properties of soapnut oil were tested at the ETA Laboratory, Chennai, following ASTM standards. Table 1 provides a comprehensive analysis of the performance characteristics of soapnut oil. The flash point of soapnut oil is recorded at 80°C, as determined using the Pensky-Martens Closed Cup method (ASTM D93). This value represents the temperature at which soapnut oil releases sufficient vapor to ignite briefly upon exposure to an open flame or spark.

The fire point, measured using the same ASTM method, is 90°C, indicating that the oil can sustain burning for more than six seconds, demonstrating its stability as a fuel. The calculated cetane index of soapnut oil, obtained using ASTM D4737 and calculated according to ASTM D976, is 44.43. The cetane index indicates the ignition quality of the fuel and suggests a moderate performance level in diesel engines.

The Gross Calorific Value (GCV) of soapnut oil, tested at 8996 Kcal/kg, represents the total heat released during complete combustion in an oxygen-rich environment, measured using the ASTM D240 bomb calorimeter method. The kinematic viscosity of soapnut oil at 40°C, recorded as 4.73 centistokes (cSt) according to ASTM D445, reflects the fluid’s flow characteristics, crucial for effective atomization in engine injectors. Lower viscosity enhances spray formation and combustion in engines. The density of soapnut oil at 30°C is measured at 0.8678 g/ml using ASTM D4052. This value is essential for accurate fuel handling, storage, and engine metering. These findings validate soapnut oil's potential as an alternative biofuel, confirming its compliance with standard testing methods and indicating its suitability for biofuel applications.

Table 1. Properties of soapnut oil

Parameter	Method	Soapnut oil
Flash point	ASTM-D93	80°C
Fire point	ASTM-D93	90°C
Calculated Cetane index	ASTM D4737 and ASTM D976	44.43
Gross calorific value	ASTM D240	8996 Kcals/kg
Viscosity @ 40°C	ASTM D445	4.73 cst
Density @ 30°C	ASTM D4052	0.8678 gm/ml

3.3. Transesterification Process

The transesterification process for making biodiesel from soapnut oil unfolds through a series of well-defined steps. Initially, soapnuts are harvested and thoroughly dried to minimize moisture content, which could hinder the oil extraction process. Once dry, the soapnuts are mechanically pressed, using either a screw press or a hydraulic press, to extract the crude oil. This oil is then filtered to remove any solid particles and undergoes a degumming process where water or a phosphoric acid solution is added to precipitate and separate impurities. After purifying the oil, it is preheated to lower viscosity and mixed with methanol and a catalyst potassium hydroxide (KOH).

The mixture is heated to about 60°C to 65°C and stirred continuously to ensure thorough mixing. This reaction transforms the triglycerides in the oil into methyl esters, which comprise biodiesel and glycerol. Once the reaction completes, the mixture is allowed to settle. The lighter biodiesel floats to the top above the denser glycerol. This top layer of biodiesel is then carefully decanted and washed with warm water to eliminate any remaining catalyst, soap, and glycerol. It is then heated to evaporate any residual water. The final stage of the process involves testing the biodiesel to ensure it meets specific quality standards such as ASTM D6751 or EN 14214. This is done by examining properties like viscosity, specific gravity, flash point, cloud point, and cetane number. Ensuring these standards are met is vital for confirming that the soapnut oil has been successfully converted into a viable alternative fuel.

3.4. Common Rail Direct Injection (CRDI) Engine Setup

The experiments were performed on a Kirloskar AV1 model, a single-cylinder, water-cooled, vertical four-stroke diesel engine. The schematic diagram of the CRDI engine setup is shown in Figure 2, and its specifications are provided in Table.2. The engine operated consistently at 1500 rpm, producing its rated power output of 3.7 kW.

Injection pressures were up to 880 MPa, with short pulse durations ranging from a few hundred to several milliseconds to maintain stable speed. The setup featured a custom-designed high-pressure fuel system driven by an electric motor-powered Kirloskar high-pressure pump running at 1500 rpm. An inlet-metering valve was used to adjust injection pressure independently from the engine speed. An additional high-pressure valve on the fuel rail ensured precise regulation. A fuel pressure sensor and a fast-response piezoelectric transducer were installed for detailed pressure data collection.

The system utilized a Bosch common rail design with four injector ports on a linear rail, capable of handling pressures up to 100 MPa and a total volume of 18 cm³. Data from the high-pressure sensor was transmitted to the engine ECU for precise control of injection pressure, fuel flow, and timing. Fuel injection was managed by a three-hole Bosch Common Rail solenoid injector, capable of operating at pressures up to 100 MPa and delivering up to four injections per cycle. Depending on pulse duration and rail pressure, the injector could inject between 0.5 and 100 milligrams of fuel per injection. It featured a reverse-leak system to return excess fuel to the tank. The high pressures required considerable force to lift the injector needle.

AVL software gathered exothermic data, including pressure trace, heat release, and burned fuel mass at 5%, 50%, and 95%. "Engine Test Express 2014" software monitored injection pressure and timing. The calculated profiles matched well with actual pressure variations during the engine cycle. Emission testing employed a smoke meter and exhaust gas analyzer, with the sampling point positioned away from the exhaust manifold for accuracy. Smoke density was measured using an AVL 415 Variable Sampling Smoke Meter, while exhaust emissions were recorded with an AVL DI gas analyzer.

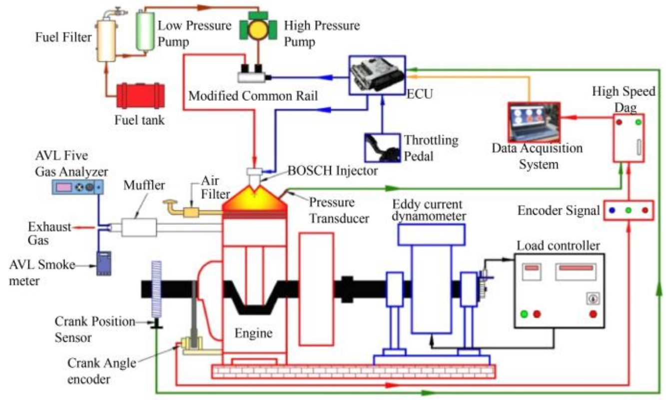

Fig. 2 Schematic diagram of CRDI engine setup

Table 2. Specifications of engine setup

Parameter	Descriptions
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

4. Results and Discussion

4.1. Brake Specific Fuel Consumption (BSFC)

Soapnut oil blends were tested to assess their impact on the fuel consumption of CRDI diesel engines under various power conditions, as illustrated in Figure 3. The results indicate a clear pattern where increasing the proportion of soapnut oil in the blend leads to higher Brake Specific Fuel Consumption (BSFC), which suggests reduced fuel efficiency.

As the percentage of soapnut oil in the blend increases, more fuel is needed to produce the same power. At the highest power level, diesel had a BSFC of 0.38 kg/kW-hr, while the values for SNT10, SNT20, and SNT30 were 0.44 kg/kW-hr, 0.46 kg/kW-hr, and 0.47 kg/kW-hr, respectively. These findings demonstrate that soapnut oil blends produce higher fuel consumption than diesel, with SNT30 being the least efficient.

4.2. Brake Thermal Efficiency (BTE)

Figure 4 depicts the variation in BTE for diesel and soapnut oil blends. The data shows that as the percentage of soapnut oil in the blend increases, the engine's thermal efficiency decreases.

This suggests that a higher soapnut oil content lowers the engine's efficiency in converting fuel energy into mechanical power. At the highest power output, diesel recorded a BTE of 25.3%, while SNT10, SNT20, and SNT30 showed BTEs of 23%, 21%, and 20%, respectively. These findings suggest that while soapnut oil is a viable alternative fuel, it leads to lower thermal efficiency than diesel at all power levels.

4.3. Carbon Monoxide Emissions (CO)

Analyzing the CO emissions for soapnut oil blends reveals notable trends, as presented in Figure.5. Soapnut oil blends, like pine oil, have distinct combustion characteristics that result in higher CO emissions than diesel. Incomplete combustion occurs more frequently when these blends do not completely mix with air or vaporize properly.

As the engine power reaches maximum power output, diesel continues to burn more efficiently with 0.52% CO, while soapnut oil blends result in 0.68%, 0.71%, and 0.73% for SNT10, SNT20, and SNT30, respectively. These results suggest that CO emissions rise as soapnut oil concentration increases, indicating a need for careful consideration of emissions when utilizing alternative fuels.

4.4. Un-burnt Emissions (HC)

Hydrocarbon (HC) emissions in Figure 6 illustrate the hydrocarbon emissions from soapnut oil blends in a CRDI diesel engine. As soapnut oil concentration increases, so do hydrocarbon emissions. At the highest power setting of 3.7 kW, diesel emits 63 ppm of hydrocarbons, while the soapnut oil blends emit 74 ppm, 78 ppm, and 81 ppm for SNT10, SNT20, and SNT30, respectively. This indicates that soapnut oil blends lead to increased hydrocarbon emissions, reflecting their less efficient combustion.

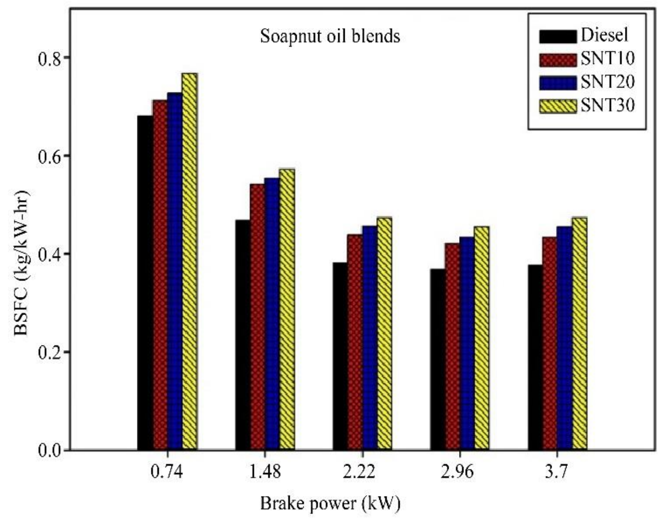

Fig. 3 Impact of Soapnut oil biodiesel blends on BSFC

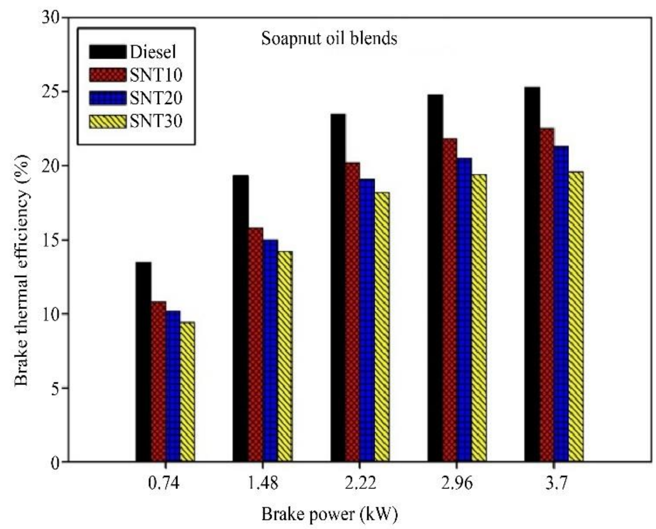

Fig. 4 Impact of Soapnut oil biodiesel blends on BTE

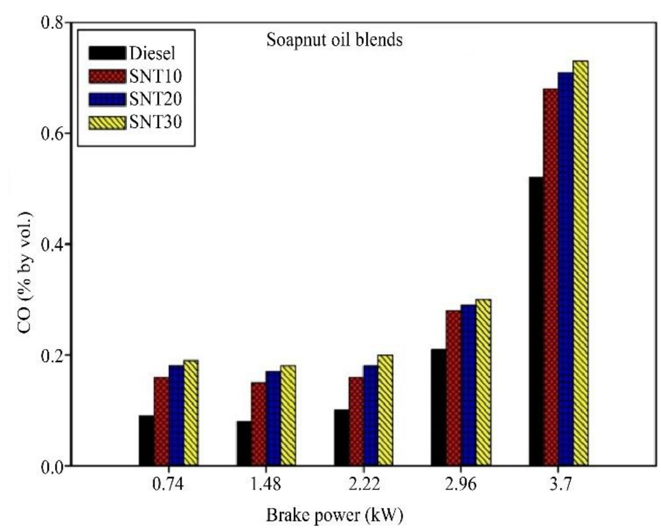

Fig. 5 Impact of Soapnut oil biodiesel blends on CO emissions

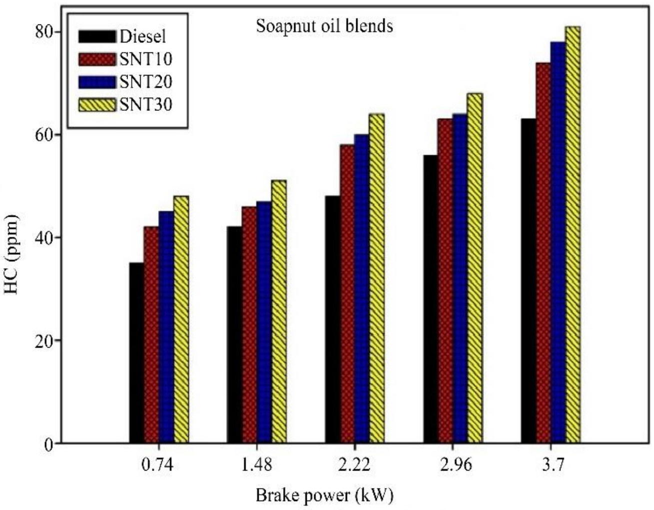

Fig. 6 Impact of Soapnut oil biodiesel blends on HC emissions (ppm)

4.5. Smoke Density

When examining smoke density, Figure 7 shows the smoke density for soapnut oil blends, which also reveals higher emissions than diesel. At 3.7 kW, diesel reaches 43 HSU, while SNT10, SNT20, and SNT30 emit 46 HSU, 47 HSU, and 48 HSU. These findings show that as the concentration of soapnut oil increases, smoke emissions rise, emphasizing the need for optimized combustion strategies to mitigate the environmental impact of alternative fuels.

4.6. Nitrogen Oxide Emissions (NO)

Figure.8 presents the NOx emissions for soapnut oil blends. At 3.7 kW, diesel emits 723 ppm, while the soapnut oil blends emit 625 ppm, 593 ppm, and 564 ppm. These results show that as soapnut oil concentration increases, NOx emissions also rise, further emphasizing the need for combustion efficiency and engine design improvements when using alternative fuels like soapnut oil.

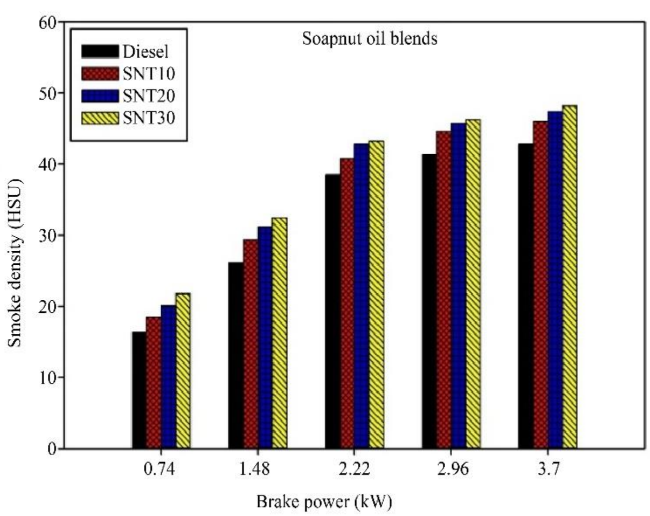

Fig. 7 Impact of Soapnut oil biodiesel blends on Smoke density (HSU)

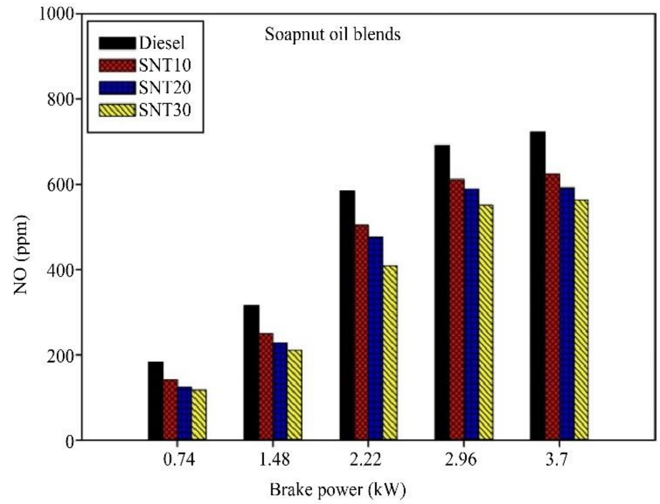

Fig. 8 Impact of Soapnut oil biodiesel blends on NOx emissions (ppm)

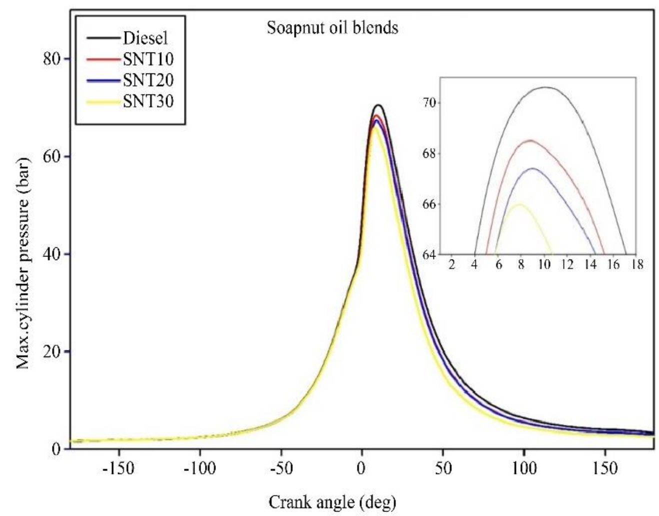

Fig. 9 Impact of Soapnut oil biodiesel blends on In-Cylinder pressures

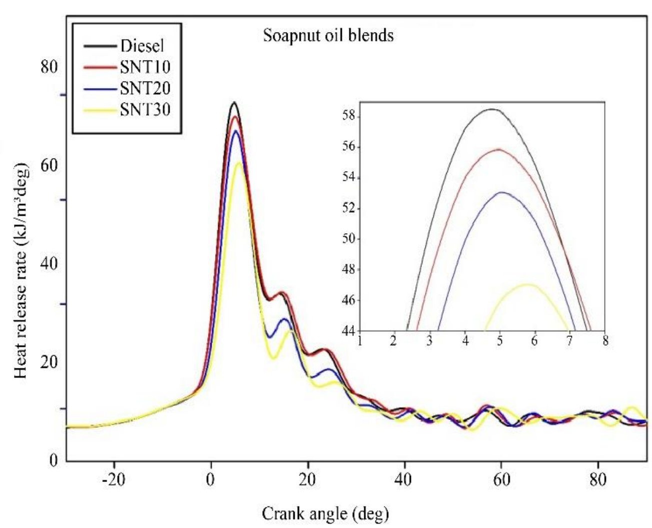

Fig. 10 Impact of Soapnut oil biodiesel blends on Heat release rate

4.7. In-Cylinder Pressure

Figure.9 displays the cylinder pressure variation for soapnut oil blends (SNT10, SNT20, and SNT30) in CRDI diesel engines. Like pine oil, the data reveals a decrease in cylinder pressure as the percentage of soapnut oil in the blend increases compared to diesel. Diesel shows the highest cylinder pressure, around 71 bar, indicating the most efficient combustion. As the soapnut oil content increases, the cylinder pressure declines. For SNT10, the pressure is slightly lower at 68 bar, indicating a marginal decrease in combustion efficiency. SNT20 shows a further drop to 67 bar, signifying a more noticeable reduction. The lowest pressure, about 66 bar, is observed with SNT30, reflecting the greatest drop in combustion performance. The drop in cylinder pressure is mainly caused by the higher viscosity and density of soapnut oil, which interfere with fuel atomization and lead to less consistent combustion.

4.8. Heat Release Rate (HRR)

Figure 10 presents the Heat Release Rate (HRR) for soapnut oil blends (SNT10, SNT20, and SNT30) in CRDI diesel engines. The HRR provides insight into the efficiency and speed of energy release during combustion. Diesel fuel exhibits the highest HRR, peaking at about 58 kJ/m³deg, which reflects its efficient combustion and rapid energy release. As soapnut oil is blended into the fuel, the combustion becomes less efficient, leading to a decline in HRR. SNT10, with 10% soapnut oil, shows a slightly lower HRR, peaking around 54 kJ/m³deg, suggesting a minor drop in combustion efficiency compared to diesel.

As the blend concentration increases to 20% (SNT20), the HRR decreases further, reaching approximately 53 kJ/m³deg, indicating a more pronounced reduction in energy release during combustion. When the soapnut oil concentration reaches 30% (SNT30), the HRR drops to around 46 kJ/m³deg, reflecting significantly slower and less efficient combustion. The lower HRR in soapnut oil blends is caused by its higher viscosity and lower volatility, affecting fuel atomization and mixing with air in the combustion chamber. Additionally, soapnut oil's lower cetane number may contribute to slower ignition, reducing the HRR.

5. Conclusion

Soapnut oil, a diesel substitute in CRDI diesel engines, offers promising yet varied effects on performance and emissions. While soapnut oil shows potential as an alternative fuel, higher concentrations in blends tend to influence fuel efficiency and emissions in complex ways. Research indicates that, though soapnut oil can help reduce nitrogen oxide (NOx) emissions, it also decreases combustion efficiency and increases fuel consumption.

- As the proportion of soapnut oil in the blend rises, there is a noticeable increase in Brake Specific Fuel Consumption (BSFC). For instance, diesel's BSFC is 0.376 kg/kW-hr; however, with a 10% soapnut oil blend (SNT10), BSFC rises by 6%. This increase continues with higher blends, with SNT20 and SNT30 showing 8% and 9% increases, respectively.
- Similarly, Brake Thermal Efficiency (BTE) demonstrates a decreasing trend. Diesel typically achieves a BTE of 25%, but with SNT10, BTE drops by 2%, SNT20 by 4%, and SNT30 by 5%. This decline indicates reduced efficiency as the concentration of soapnut oil in the blend grows.
- Emission analysis reveals a significant increase in carbon monoxide (CO) emissions when soapnut oil blends are used. CO emissions increased by 16%, 19%, and 21% for SNT10, SNT20, and SNT30, respectively, compared to diesel's baseline CO emission rate of 0.52%. Likewise, hydrocarbon (HC) emissions and smoke density increase with higher soapnut oil content. HC emissions rise by 11%, 15%, and 18% for SNT10, SNT20, and SNT30, respectively, and smoke density follows with 3%, 4%, and 5% increases.
- On the other hand, NOx emissions tend to decrease with a higher concentration of soapnut oil. Starting from a baseline NOx emission of 723 ppm with pure diesel, the levels decrease by 9.8% for SNT10, 13% for SNT20, and 16.9% for SNT30.
- Furthermore, both in-cylinder pressure and Heat Release Rate (HRR) are reduced as the blend percentage of soapnut oil rises. In-cylinder pressure shows reductions of 3%, 4%, and 5% for SNT10, SNT20, and SNT30, respectively, while HRR declines by 4%, 5%, and 6% across the same blends.

In conclusion, while using soapnut oil in diesel blends can lower certain emissions like NOx, it may negatively impact other aspects of engine performance, such as fuel efficiency, overall combustion efficiency, and other emissions.

These findings underscore the need for further research to optimize the blend of soapnut oil in diesel, aiming to balance its environmental benefits with performance requirements.

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