Journal of Mines, Metals and Fuels, *73(11): 3607-3616; 2025. DOI: 10.18311/jmmf/2025/50076*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Unlocking the Potential of Simarouba Glauca Seed Oil as an Alternative Fuel in Diesel Engines

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Abstract

This paper examines the performance of a compression ignition engine using raw Simarouba Glauca Seed Oil (SGO) blended with petro-diesel. Diesel fuels like SGO10 (10% SGO + 90% diesel), SGO20, SGO40, SGO60 and SGO100 (100% SGO) were used for this study. Tests were conducted under four loading conditions (0%, 25%, 75% and 100%). This study revealed that raw SGO blends can be sustained by a CI engine, and that there is no need for specific modifications to engine operations. These results indicate that higher SGO blends create incomplete combustion and a loss of some performance. Compared with diesel, the SGO blends gave Brake Thermal Efficiency (BTE) values that were 4-9 % lower and Brake Specific Energy Consumption (BSEC) values that were 4-9 % higher at higher loads. In addition, in SGO blends, the Net Heat Release Rate (NHRR) dropped by 15–48 % and the Cumulative Heat Release Rate (CHRR) dropped by 1.8-15.7 %. Emission studies showed NOx emissions were reduced by about 20% compared to diesel fuel, while hydrocarbon emissions were slightly higher.

Major Findings: *Raw Simarouba Glauca Oil blends can be used in Compression Ignition (CI) engines without modification, especially at lower blend ratios. Higher blends reduce performance due to incomplete combustion but significantly lower NOx emissions (by ~20%). BTE decreased by 4-9 %, while BSEC increased by 4-9 % at higher loads.*

Keywords: *Diesel Engine, Emission, Engine Characteristics, Simarouba Glauca Oil*

1.0 Introduction

The energy sector has a significant impact on the growth and development of a nation. Trends related to industrialisation and automation all over the world have resulted in a steep increase in energy needs. With the yearly increase in energy consumption, carbon dioxide emissions from the combustion of fossil fuels exceeded 38 billion tons in 2019.

Worldwide energy use is projected to increase by over 25% by 2040. Many industries, such as manufacturing, transportation, and energy generation, account for a large part of energy consumption. Vehicle fuel makes up around 24% this demand, with 66% diesel. Energy

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issues are the rapid exhaustion of fossil fuel reserves, the increase in environmental awareness, doubts about the reliability of energy supply, fluctuations in energy availability for consumers, and frequent increases in the cost of gasoline and diesel fuel[1]. Among the sustainable and environmentally friendly replacements, vegetable oil has a number of advantages over petroleum products. The following advantages need to be highlighted: higher thermal efficiency and low sulphur concentration, natural biodegradability and less generation of carbonaceous gases[2]. At the same time, in the face of the problem of securing energy resources, plant-based oils, both edible and inedible, in addition to bioenergy oils, and other wastes that are widespread and have no other capacity than to accumulate, as fuel in diesel engines, were thoroughly investigated.

However, plant-based oils are less volatile yet more viscous, so engines that use them can suffer from performance issues. One of the many types of high-oil, non-edible vegetable oils is Simarouba Glauca Oil (SGO), also known as Simarouba seed oil. In India, some 55.76 million acres of land remain uncultivated, with Tamil Nadu accounting for 17.95 million acres of this oil. Simarouba farming, as such, provides a more economical long-term solution for biodiesel production in these areas. Despite its potential, the food and pharmaceutical industries continue to largely disregard SGO. Simarouba is a multipurpose tree that thrives very well in arid land, resists temperatures up to 45°C, and can grow excellently in nutrient-lacking soil. From approximately 22kg of nutlets, a single well-grown tree produces about 5kg of oil, as well as an equal weight of by-products. The extract solid content is more than 60% in Simarouba seed. On a large scale, 2000kg of oil and equivalent oil cakes can be produced from one acre of land[3].

A study shows that a compression ignition engine with one cylinder fed with 50% Simarouba oil methyl ester gave 22% lower smoke pollutants and 33% lower Hydrocarbon (HC) emissions. Another test indicated that a 50% blend of eucalyptus and Simarouba oil performed better, had better ignition characteristics, and produced fewer emissions[4].

Recent studies have concluded that SGO can be a viable feedstock for biodiesel production and may soon replace diesel fuel[5,6]. However, more investigation is needed to completely understand its combustion, performance, and emission properties. The vast exploration of raw Simarouba Glauca Oil in various proportions with petro-diesel as blends has not yet been investigated, and its feasibility is yet to be known. This study aims to provide an overview of the potential of using SGO as a substitute for diesel and the best blend of SGO to diesel that would yield satisfactory engine conditions, and any necessary modifications required to be made.

2.0 Resources and Procedures

2.1 Vegetable Oil Extraction

Simarouba Seed Oil: The seeds used to make the Simarouba seed oil were sun-dried and processed in Gujarat, India. Figure 1(a) displays the manual peeling of roasted Simarouba fruit, while Figures 1(b) and 1(c) denote the removal of the outer layer and its hard seeds respectively[7]. Oil was pumped from the ground using a motorised screw pump.

The amount of glycerol in SGO is the most important hindrance in biodiesel preparation in the presence of impurities. To refine the oil, hexane was added and swirled for 10 to 25 minutes while the SGO was heated to



Figure 1. **(a)** Broken fruits, shells, and kernels of the Simarouba tree, **(b)** Simarouba tree seeds before decortication, **(c)** Seeds after decortication.

25-45 °C. After cooling for 30 minutes (the time needed for the hexane to evaporate), the impure particles sank to the bottom of the mixture and were removed. SGO contains about 4% Free Fatty Acids (FFA), which are expressed as a proportion of oleic acid. As a result, a primary transesterification procedure as well as an initial pre-treatment were conducted.

2.2 Fuel Properties

Simarouba seed oil, due to its high viscosity, is blended with diesel in various ratios to test engine performance. Table 1 shows the fuel blend properties compared to American Society for Testing and Materials (ASTM) standards.

The fuel blends are characterised by key physical and chemical properties, including kinematic viscosity, calorific value, pour point, pH, fire point, and flash point. Fuel cloud point and density value are a few other important factors. Since SGO has higher flash and fire points than diesel, it is more stable, as shown in Table 1. Although this is good for lubricating, its high viscosity can impede atomisation and cause incomplete combustion. SGO has a molecular-weight range extending from 600 to 900, roughly 12 times the molecular weight of diesel, compromising its combustibility due to the high viscosity.

Since SGO is viscous, its density is approximately 7.8% heavier than the specific gravity limits of petro-diesel, which is between 0.80 and 0.86. Due to its higher boiling point, incomplete combustion and fuel impingement further impact engine performance. According to Table 1, the thermal energy values of SGO and diesel show that SGO has approximately 8% lower energy than diesel. However, its natural lubricating qualities and fuel-bound oxygen concentration can compensate for this energy deficit and increase engine performance and combustion efficiency[8].

The acid value of a lipid is the quantity of KOH needed for the neutralisation of one gram of FFA. Maximum acid concentration of 0.5mg KOH/g was observed from the American Oil Chemists' Society (AOCS). This number, known as the Neutralisation Number (NN), gives information on how effective a lubricant is during use and for how long the lubricant stays effective. The NN of Simarouba Glauca Oil (SGO) is found to be 6.9348mg KOH/g, which is much higher than the proper issues limit and restores the oil's steadiness and liveliness in many engine instances.

2.3 CI Engine Experimentation Approach

A single-cylinder using water as a coolant diesel engine, illustrated in Figure 2, was used for testing. Selected important engine parameters are listed in Table 2. Smoke emissions were also assessed using an AVL 437 smoke meter, and the constituents in the exhaust were examined using a gas analyser, AVL Di-gas 4000. Initially, the engine was run on diesel fuel until it smoothed out.

Table 1. Characteristics of Simarouba Glauca Oil

Fuel Property	Diesel (ASTM D975)	Simarouba Oil (SGO)	Biodiesel (ASTM D6751)	Test Method
Heating Value(kJ/kg)	43,000	39,229	-	D240
Kinematic Viscosity at 40°C (cSt)	1.9 - 4.1	45.75	1.9 - 6.0	D 445
Boiling Point(°C)	197	271	37 - 285	D86
Ash Content wt. (%)	0.01	0.005	<0.02	D 482
Sulfur wt. (%)	0.045	0.016	0.050max.	D 2622
Acid Value (mg KOH/g)	0.05	6.9348	0.8 max	D664
Pour Point (°C)	-35 to -15	19	-15 to 16	D 97
Carbon Residue wt. (%)	0.35	1.56	0.050 max.	D 2500-05
Fire Point (°C)	72	342	-	D92
Flash Point (°C)	45 - 60	258	100 - 170	D93
Density at 30°C (gm/cc)	0.830	0.909	0.86 - 0.90	D 4052
Cloud Point (°C)	-15 to 5	25	-3.0 to 12	D2500

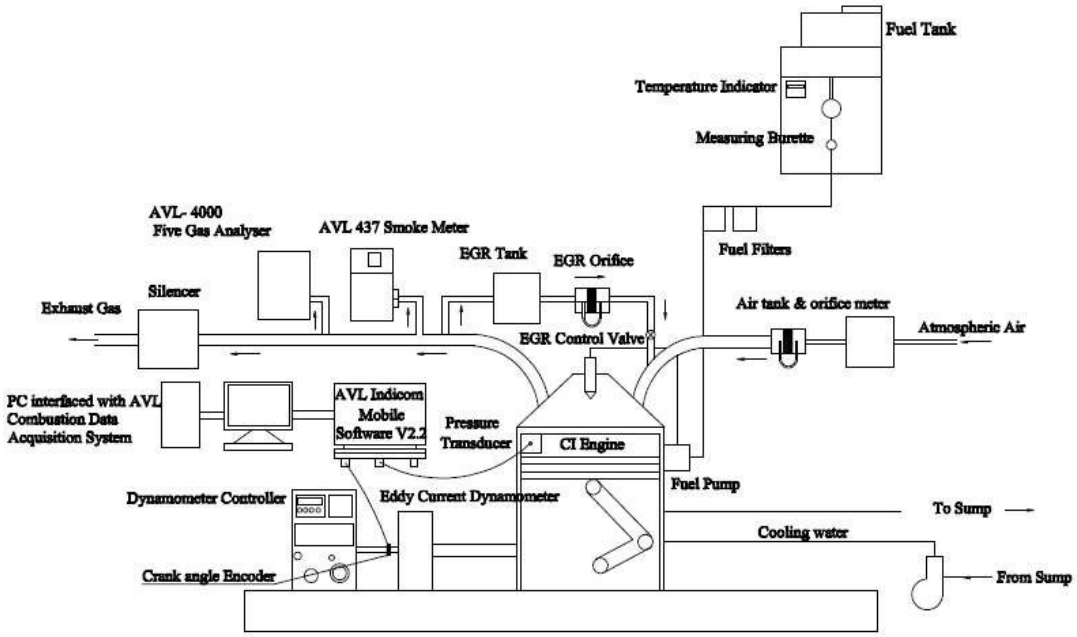


Figure 2. Diagram design of investigational arrangement.

Table 2. Engine technical specifications

Make	Kirloskar
Type	Single Cylinder, Four stroke, Direct Injection
Number of Cylinders	1
Displacement (cm^3)	661
Speed (rpm)	1800
Bore and Stroke (mm)	87.5 x 110
Cooling System	Water cooling
Rated Power (kW)	5.9
Connecting Road Length (mm)	185
Injection Timing	23° bTDC
Dynamometer Type	Eddy Current
Compression Ratio	17.5: 1
Injection Pressure (bar)	200
Lubrication System	Forced Feed System

For every fuel blend, engine pollutants, air fuel ratio, and Exhaust Gas Temperature (EGT) were measured. Data were averaged over three time periods. A System for acquiring computational data (DAQ; AVL INDISMART 612), capable of processing and storing a maximum of 1000 cycles of data, was used to obtain engine data, especially cylinder pressure readings.

Diesel engine efficiency, combustion performance, and emissions were evaluated in accordance with the guidelines given by ISO/IEC 17025 and National Accreditation Board for Testing and Calibration Laboratories (NABL 141).

The uncertainty analysis of the experimental trials was performed using the Guide to the Expression of Uncertainty in Measurement (GUM) method for data evaluation. Errors and percentage uncertainty were calculated taking into account workplace conditions, tool choice, and measurement accuracy and dependability. The uncertainty of different performance parameters is in % and was calculated based on accuracy, precision and the resolution of the laboratory equipment. In order to reduce risk exposure, Table 3 additionally assessed the accuracy of the data. A 95% confidence level linear and standard distribution was chosen for the highest level of accuracy and precision in uncertainty estimation.

$$U_{combined} = \sqrt{(U_{repeatability})^2 + (U_{accuracy})^2 + (U_{resolution})^2 + (U_{precision})^2 + (U_{calibration})^2}$$

$$U_{expanded} = \frac{U_{combined}}{2}$$

Table 3. Uncertainty analysis of engine performance and emissions

S. No.	Engine Characteristics	Experimental Percentage Uncertainties
1.	Brake Power	±3.17
2.	Speed of the engine	± 0.46
3.	Brake specific fuel consumption	±3.75
4.	Smoke	±1.7
5.	Engine Load	± 2.29
6.	Unburned Hydrocarbon	±5.6
7.	Oxides of Nitrogen	±0.89
8.	Total Fuel Consumption	±1.01
9.	Carbon Monoxide	±3.9
10.	In-Cylinder Pressure	±1.20

3.0 Results and Discussions

3.1 Performance Parameters

This sub-section discusses the corresponding efficiency for the CI engine in which different fuel blends are tested. Fossil diesel fuel was the standard reference for the performance and pollutant assessment.

3.2 Thermal Efficiency at the Brake Output

It can be understood from Figure 3 that the BTE for raw Simarouba Glauca Oil (SGO) was found to be less than fossil diesel under 100 per cent load conditions.

Under a 5kW load, the BTE of SGO10, SGO20, SGO40, SGO60, and SGO100 was 4.11%, 4.50%, 6.09%, 6.71%, and 9.00% lower than that of pure diesel. In a similar pattern, the blended raw oil resulted in reduced brake thermal efficiency of approximately 11.08-18.05 % and 8.46-12.72 % in comparison with diesel fuel for loads of 1.75 kW and 3.5 kW, respectively. Since the density and viscosity values are high for SGO oil, and the special distillation property of improved generation of spray, air-fuel mixing, high volatility and lower calorific value of SGO, BTE fell. Segments of SGO combustion are less efficient than diesel due to its deeper fuel penetration and narrower spray cone angle. The BTE value dropped distinctly as the raw oil proportion of the blend increased. However, when the load went up, the percentage drop in BTE decreased as the temperature

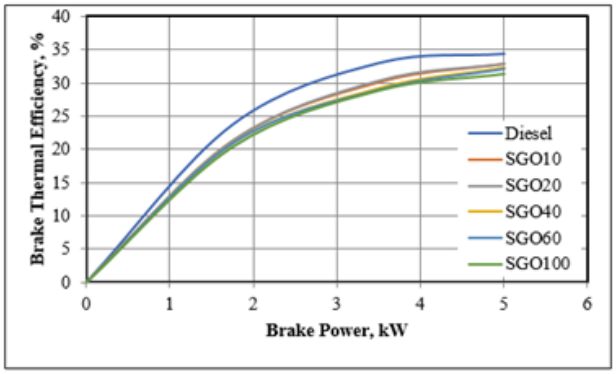


Figure 3. Variation of brake thermal efficiency with brake power.

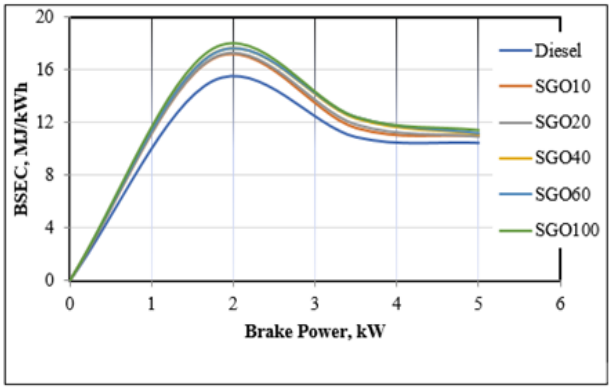


Figure 4. Brake specific energy consumption versus brake power.

in the combustion chamber rose, which enhanced the atomisation process[9].

3.3 Brake-Specific Energy Consumption

BSEC is a reliable measure for evaluating the test blends, especially when there are notable differences in density and heating value. As shown in Figure 4, the BSEC of SGO10, SGO20, SGO40, SGO60, and SGO100 was, on average, 4.9%, 4.7%, 6.5%, 7.2%, and 9.4%, respectively, higher than diesel (5kW load).

In the same way, the BSEC as compared to diesel increased by about 11-16.3 % and 6.3-14.1 % for 1.75kW and 3.5kW loads, respectively, for the SSO oil blends. Conclusion from the pattern is that efficiency shoots up and BSEC is decreasing with rise in load, hence, proper combustion is taking place at higher loads. This means that an increased combustion chamber temperature at elevated loads leads to improved energy utilisation due to superior atomisation and fuel-air dispersion[10].

3.4 Ignition Features

The combustion properties, in-cylinder pressure, rate of heat release, ignition delay, duration in combustion, and mass burned fraction of SGO and diesel fuel were investigated and analysed.

3.5 Cylinder Pressure

Figure 5 shows the crank angle vs pressure developed inside the cylinder for SGO blends at a load of 5 kW because of its elevated calorific value and superior autoignition properties. Diesel fuel recorded the highest peak pressure of 64.28 bar.

Conversely, SGO blends produced lower peak pressures than diesel. The maximum cylinder pressures of SGO10, SGO20, SGO40, SGO60, and SGO100 were of 63.654, 62.511, 62.233, 61.931, and 61.15 bar, respectively. These were lower than diesel by 0.97%, 2.75%, 3.18%, 3.65% and 4.86%, respectively. This decrease in peak pressure is more pronounced since simarouba oil molecules have higher viscosity and lesser volatility, which leads to insufficient atomization and suboptimal air-fuel mixing efficiency[11].

3.6 Rate of Net Heat Release

Figure 6 presents the two stages of combustion during burning. The calculated NHRR value for SGO10, SGO20, SGO40, SGO60, and SGO100 was 15, 30.1, 30.4, 42.5, and 48.1% lower than diesel at 5 kW load, respectively. As the fuel blends increased, the amount of raw oil also increased, which led to extending the diffusion combustion phase and reducing the NHRR.

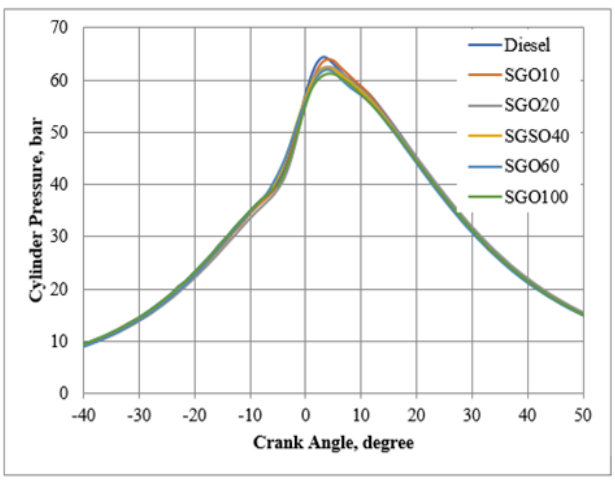


Figure 5. Cylinder pressure with crank angle.

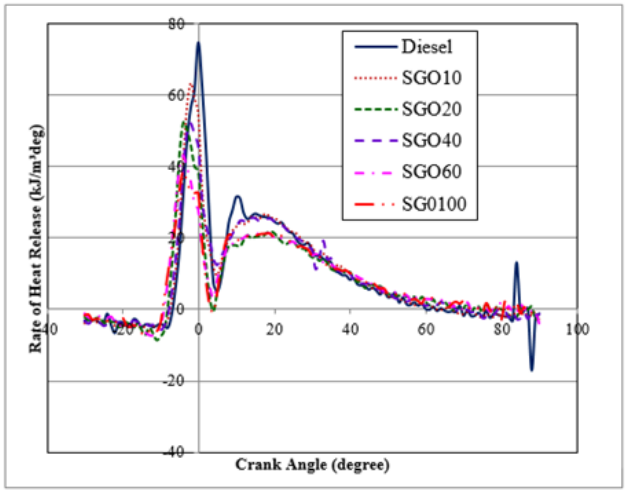


Figure 6. Heat release rate as a function of crank angle.

With a shorter Ignition Delay (ID), diesel shows a high-premixed HRR at the start of mixing, which gives a good air-fuel formation. In contrast, higher oxygen fuels, such as slags with SGO mixtures, promote the full combustion of fuel left over from the first stage and sustain the combustion process in the next combustion stage[12].

3.7 Cumulative Rate of Heat Release

Figure 7 displays how the SGO fuel is converted to efficiency, as indicated by the CHRR was studied. Suggesting that the ability of SGO mixes to transfer heat energy became less efficient, the CHRR values for SGO10,

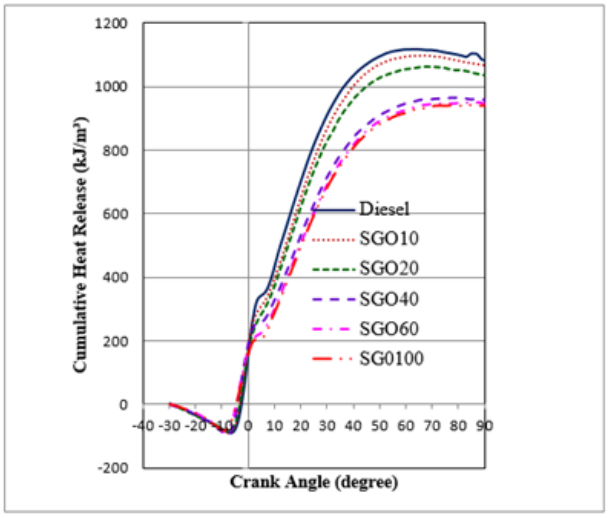


Figure 7. Total heat release over crank angle.

SGO20, SGO40, SGO60, and SGO100 were 1.8%, 4.9%, 13.8%, 15.1% and 15.8% lower than those of diesel, respectively.

The 5-kW load with a higher SGO mix exhibited greater CHRR reduction than diesel. However, the higher concentration of oxygen in the SGO oil mixes aided the flame movement and increased ignition rates, and compensated for reduced heat conversion efficiency. Similarly, using kerosene and canola oil in a diesel engine produced similar results when tested[13]. One more key attribute of the combustion time, as given in Figure 8, is the Ignition Delay (ID), which is described as the time duration from when the fuel is injected to the moment when 5% of the fuel mass is burnt.

The dependency of ID on SGO content is to some extent because with increasing SGO content, factors like higher Cetane Number (CN), more fuel accumulation when the first burning process, increased viscosity and decreased fuel movement come into play, causing an exponential fall in ID[5]. At low loads, SGO10 is slightly better than diesel. SGO blends appear reduced in ID as compared to diesel; enhancement of viscosity appears to produce a shortening of time delay.

3.8 Emission Parameters

This section presents the comparative analysis of different engine pollutants, including Unburned Hydrocarbons (HC), Carbon Dioxide (CO_2), smoke emission, nitrogen oxides (NOx), Carbon Monoxide (CO) and EGT for the tested blends in Table 1.

3.9 Hydrocarbon Emission

Figure 8 reveals that SGO blends exhibited lower UBHC emissions than mineral diesel. At 5kW, the UBHC emissions of SGO10, SGO20, SGO40, SGO60, and SGO100 with respect to pure diesel were 18.75% 28.23% 12.5% 15.63% and 28.13% greater, respectively. By contrast, the UBHC emissions in raw oil blends were increased by approximately 12.5%–37.5% and 7.4%–29.6% at 1.75kW and 3.5kW loads, respectively, than the base fuel.

The surge in UBHC emissions may be because of the larger viscous nature of SGO, which prevents appropriate atomisation and burning. In addition, the low volatility of SGO could have lowered spray generation within the combustion chamber, causing slower combustion and high HC emissions. Also, increasing loads and

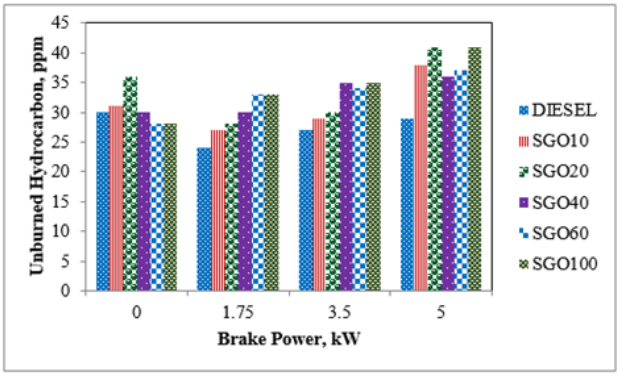


Figure 8. Unburned hydrocarbon emissions versus brake power.

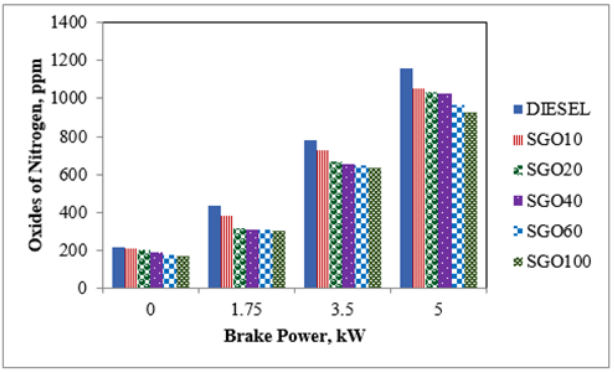


Figure 9. Oxides of nitrogen with brake power.

SGO density will cause an increase in emissions. High loads increase fuel supply, but a lack of oxygen reduces combustion efficiency significantly.

3.10 Nitrogen Oxide Emissions

By comparing Figure 9, we can see that Nitrogen Oxide (NOx) emissions from SGO blends were much smaller than base fuel. At a 5kW load, the nitrogen oxides for SGO10, SGO20, SGO40, SGO60, and SGO100 were decreased by 9.22%, 10.86%, 11.38%, 16.64%, and 20% respectively, with respect to diesel. Similarly, at 1.75kW and 3.5kW loads, blends of vegetable oil produced approximately 12.39%-31.19% and 7.53%-18.75% lesser NOx emissions than diesel.

Using SGO diesel blends lowers the combustion temperature due to a change in the local stoichiometry, ignition delay, and reaction time of the mixture, which reduces the NOx emissions. Moreover, the higher viscosity of simarouba oil mixes can lead to a greater degree of incomplete combustion, thus reducing NOx emissions.

This means that SGO and its blends can be used as an alternative fuel for diesel engines, with the possibility of reducing NOx emissions[14].

3.11 Carbon Monoxide Emissions

Figure 10 indicates that SGO blends produce CO_2 emissions that vary depending on crude oil composition. At a load of 5kW, SGO10 decreased CO emissions by 20% while SGO100 increased them by 20% compared to diesel. Likewise, NMHC emissions increased by 23%-74% and 24%-48% when testing crude oil blends at 1.75kW and 3.5kW loads compared to diesel, respectively. The non-ideal atomisation and burning of crude oil blends due to their greater viscosity leads to greater CO_2 emissions. Improved mixing of fuel and air in lower-percentage SGO blends helps reduce CO emissions if CO emissions are increased at lower loads due to a lower optimum temperature and A/F ratio.

Higher A/F ratios with ignition heat produce lower CO emissions at medium loads. However, at 5kW load, CO emissions seem to rise due to the formation of Fuel-bound tiny particles in the burning zone that do not participate in the ignition process. This is due to oxygen molecules creating better combustion, even in fuel-rich areas, which allows the ignition mix to behave like a diesel[15-17]. Also, specific fuel components can promote fuel heating through the consumption of excess oxygen and prevent complete combustion, leading to increased carbon monoxide emissions.

3.12 Carbon Dioxide Emissions

Crude oil mixes emit significantly less carbon dioxide than pure diesel for lower and middle loads, as Graph 11 shows. Compared to diesel, blends with crude oil reduced the CO_2 emissions at 1.75kW and 3.5kW by 9.98-14.80 % and 3.98-8.26 %, respectively.

This counter-intensity is primarily because the combustion is incomplete, as SGO blends have a high viscosity, leading to poor atomisation[18]. Figure 11 shows the carbon dioxide with brake power analysis. For a 5kW load, SGO blends showed 1.2-3.6 % higher CO_2 than diesel. The increase is likely owing to higher CO conversion, which leads to more complete fuel burning.

3.13 Smoke Opacity

According to the results in Figure 12, raising the SGO ratio in the mixture led to growing carbon emissions. Under 5kW working conditions, smoke emissions of SGO10, SGO20, SGO40, SGO60, and SGO100 were 0.13%, 2.69 3.49%, 3.49%, and 10.75% respectively increased than that of diesel. Higher concentrations of SGO mixes are likely lacking in fundamental efficient oxygen molecules to complete this cycle[19].

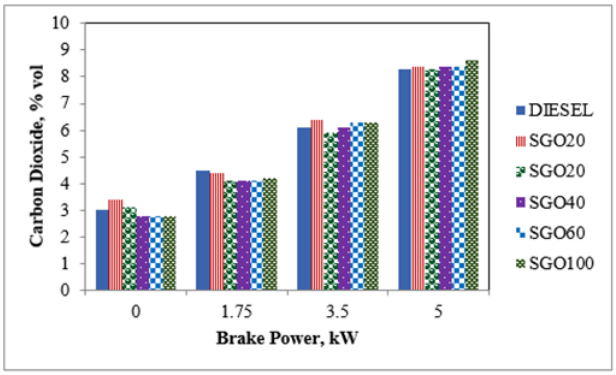


Figure 11. Carbon dioxide with brake power.

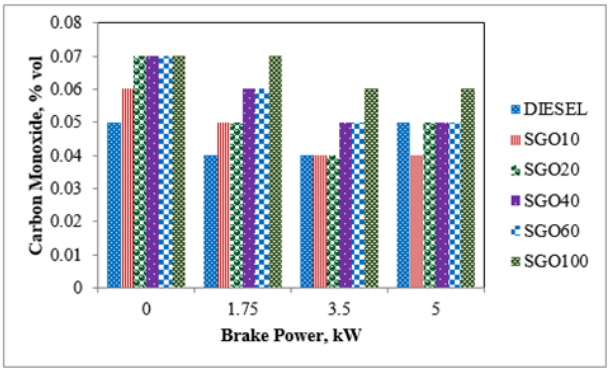


Figure 10. Carbon monoxide with brake power.

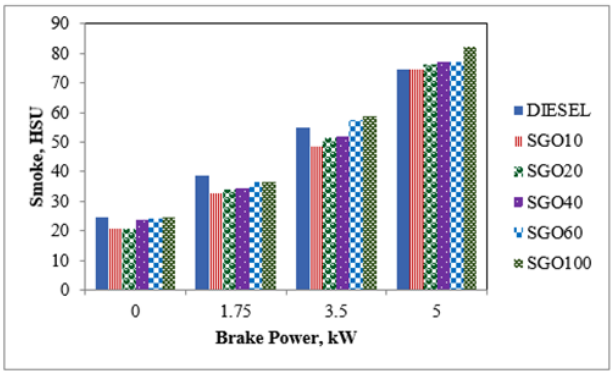


Figure 12. Smoke opacity with brake power.

Smoke is influenced by two factors: cylinder peak temperature and absolute Air-Fuel ratio (af). Local smoke formation behaviour varies from low to high load, indicating that when the proportion of Air to Fuel in specific regions of the spark zone is lower than the conceptually optimum mixture, smoke emissions increase significantly in both normal and maximum load conditions[20].

4.0 Conclusion

An engine can be properly operated by natural Simarouba fuel without the need for any modification. Despite this being the worst solution for combustion efficiency for standard diesel in a diesel engine when using SGO. Features such as shorter ID, longer Combustion Duration (CD), lower chamber pressure, and HRR numbers are evident. SGO methyl ester meets ASTM specifications and exhibits properties like diesel fuel. SGO10 recorded a BTE 4.5% lower than that of diesel, with further blends presenting even lower BTE levels. Furthermore, SGO10 requires 4.8% more energy compared with diesel.

At 5 kW load, SGO Nox emissions were around 7% higher and some up to 20% lower. Diesel had lower CO emissions than most of the raw oil mixes, except for SGO10. Other compounds such as alcohols, oxidisers and metallic boosters could be explored to facilitate the combustion process and lead to lower emissions. Further research is needed to assess the future effects of raw SGO on fuel injection systems and engine components.

Moreover, raw SGO reserves need to be substantiated for reliability, and the large-scale production needs an economic viability test.

5.0 Future Scope

This study will help to reduce the trend towards higher raw oil constituents in Compression Ignition engines, and perhaps additives such as alcohols, oxidisers and metallurgical modifications in the longer term could form avenues for avoiding higher raw oil concentrations. More research is needed to fully understand the enduring effect of unprocessed SGO on fuel delivery mechanisms and components of engines. Further research is needed to determine the commercial viability of manufacturing and the long-term stability of raw Simarouba oil and biofuel.

Due to simarouba oil's exceptional oxygen content, due attention must be given to emission control technologies, such as recirculation of engine exhaust gas, water injection, to prevent the anticipated increase in oxides of nitrogen emissions. The cold flow properties of this oil can further be enhanced by additives or blending techniques to improve its usability in colder environments. Some provide dosages of fuel-borne nanoparticles (e.g., cerium oxide, alumina particles), which improve combustion efficiency and emission performance.

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