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A Critical probation for potentiality of bio-fuel with exquisite concoction of natural anti-oxidant additive in engines for pollutants reduction

Sithivinayagam N.[1]* and Anandavelu K.[2]
[1]Department of Mechanical Engineering, Anna University Chennai, Tamil Nadu, India
[2]Department of Mechanical Engineering, M R K Institute of Technology, Tamil Nadu, India
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*to whom all correspondence should be addressed: e-mail: sithimrkit2023@yahoo.com
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Graphical abstract

Abstract

Considering the present global fuel scenario, it becomes highly inevitable to opt for biofuel. Yet the use of biodiesel had increased pollutants which are emitted to the atmosphere such as Carbon monoxide, Unburnt Hydrocarbon, Nitrogen oxides and Smoke density in the combustion products. For this analysis, a novel and naturally obtainable antioxidant (Coffea Arabica antioxidant) has been experimented. With POME20 (20% palm oil Methyl ester and 80% diesel fuel), a proportion yielding favorable results based on several studies, Coffea Arabica antioxidant additive was infused in different proportions (ppm's) to obtain the test blends. The thus derived blends PSBC500, PSBC1000, PSBC1500 and PSBC2000 in addition to plain DF and POME20 were used in diesel engine that is of the type, single cylinder DI water cooled TV-1 Kirloskar, under different load conditions. The test results showed improved BSFC and BTE for Coffea Arabica antioxidant infused blends. The atmospheric pollutants emitted from the engine such as CO, UHBC, NOx and SD were reduced considerably for the antioxidant additive infused POME20 blends simultaneously not creating any adverse impact in the performance of the engine. Among the test blends, PSBC 2000 was found performing with the closer tolerating characters as the plain diesel fuel.

Keywords: Air pollution, palm oil, coffee leaf, anti-oxidant, additives

1. Introduction

Rudolf Diesel was a pioneer in using biodiesel in CI engines at the beginning of the 19th century. Many nations began focusing on the impacts of biodiesel in diesel engines as a result of the shortages of crude oil that occurred between 1970's and 1980's. The research investigators are concentrating on resources of biomass as supplementary oil for diesel in IC engines specifically in transportation and industrial sectors because of the rising global energy demand in an shocking rate and also due to the concerns on human health, economy, and global environment. By using fossil fuels for transportation, pollution is produced.

A major issue is global air pollution. As a result, alternative fuel for engines and fuel systems must be designed so that they can produce enough power while yet adhering to legal emission restrictions. The internal combustion engine has undergone a considerable deal of development and research. Since biofuel's qualities are so similar to those of diesel fuel, most studies have fixed that it has prospective as an alternative fuel for diesel engines [Canakei M. *et al.* (2003); Chang D.Y.Z. *et al.* (1996); Freedman B. *et al.* (1983)]. Without many changes or with some, bio-fuel can be utilised in diesel engines. The resin and seeds of plants are used to make this bio-fuel. It is well known that plant oils are low in sulphur and renewable. Because biofuels are more expensive than fossil fuels, the widespread use of biodiesel has been constrained [Choi C.Y. *et al.* (1997), Mayer – Pitroff R. *et al.* (1995)]. A suitable fuel is also being sought after as part of the study process.

In the effort to create a more environmentally friendly world, palmyra oil is being proposed as supplementary oil for traditional fuel in diesel engines. There are certain biomass varieties which are undoubtedly a feasible feedstock for the biofuel production due to the abundant supply of this feedstock on a worldwide basis. By adding additives, it is possible to reduce emissions further while also improving performance. Several experimental investigations have reported the infusion of metal-based additives for examining the engine performance and emission levels. In this research analysis, natural antioxidant additive extracted from coffee leaf pigment is used to blend with methyl ester palm oil and diesel fuel.

The some of the benefits of using biofuel are liquid nature portability, quick accessibility, higher heat content, renewability, higher cetane number, higher flash point, lower sulfur and importantly biodegradability and aromatic content. The authors [Husna K. *et al.* (1995)] investigated effectiveness of 20% palm seed methyl ester and 80% of diesel (POME20) over the blends in different ratios. Authors [Qiu. X. *et al.* (1996)] have also reported that BTE was higher for the blend, POME 20 when operated at full load and it is 26.63% as compared to other blends and diesel fuel i.e., POME10, POME30, POME40 and diesel fuel with 21.28%, 22.50%, 21.19% and 25.13% respectively. The BTE of POME20 operated at different load conditions shows a slightly higher value than diesel at all load conditions. From the above author's investigative analysis and various literature survey pertaining to palm seed oil, it is observed that the POME20 blend has close tolerating property as standard diesel fuel. POME20 is therefore considered to be the ideal blend due to its improved performance and emission characteristics and this blend has the potential to use as partial replacement fuel for diesel.

However, the use of biodiesel increases the content of Nitrogen oxides (NOx) in combustion products. The most important factors that involves in NOx formation are flame temperature of the combustion, reaction time and importantly the level of oxygen presence in the fuel. This was happened because of the excessive oxygen presence of the biodiesel blends. The reduction in NOx emission is possible by adding antioxidant additives in the biodiesel blends. And so, it becomes imperative to use antioxidant additives that too naturally extractable to lessen the emission pollutant levels. Antioxidant extracted from Coffea Arabica L in different ppm's with POME20 blend is taken for this research analysis

2. Biofuel production

"Borasus," Greek terminologies which translate to "fruit with a leather covering," and "Flabellifer," which translate to "fan-bearer," are the origin of the name Palmyra. Spherical fruits with a diameter of 15 to 20 cm and an average weight of 1.5 kilogrammes are produced by female inflorescences. A mesocarp pulp that is yellowish in colour and edible which surrounds of three hard-coated seeds. At rare cases there will be four seeds. Figure 1 illustrates the method used to extract raw palmyra crude oil from the fruit. Worldwide 100 million Palmyra is produced each year, but only 5 to 10 million of those are really eaten. The remaining are dried and the dried palmyra seed kernels are the source of palmyra oil. Ash content in palmyra palm nuts is 0.8%, protein content is 0.18%, fibre content is 0.260%, lipid content is 0.090%, and amylase content is 26.18%.

The ASTM standards were used to determine the various physico-chemical properties is indicated in the Table 1, and it was found that palm oil had a higher viscosity and density as compared to diesel fuel.

Figure 1. Raw palm oil production

Table 1. Physico-chemical properties of Palm oil, diesel and Indian requirements as per IS 1460-1974

Properties	Palm oil	Diesel	Indian requirements as per IS 1460-1974
Density @ 40°C in gm/cc	0.904	0.827	Nil
Kinematic viscosity @ 40°C in CST	7.8	3.34	2.0–7.5
Flash point in °C	183	54	38
Fire point in °C	177	59	6 max.
Heating value in kJ/kg	35980	42650	-
Calculated cetane number	46	55	42

For this experimental work, biodiesel is obtained from Palm seed. First palm seed oil is obtained from palm seeds. Later the oil is trans esterified to get palm seed methyl ester. 3 moles of methanol and 1 mole of triglyceride are combined to form trans-ester. The reaction was delayed due to mass transfer restrictions, primarily due to the partial solubility of methanol in the oil and then due to the non-soluble nature of glycerin which is present in the methyl esters. Without agitating the catalyst is non-reactive since it tends to concentrate in the glycerin. The procedure of palm seed biodiesel preparation is as represented in Figure 2. Sodium hydroxide (catalyst) of the quantity 0.8% of PSO was dissolved in the methanol at an amount of 25% of PSO by whirling or hand shaking process. Then the alcohol catalyst mixture was discharged into a conical flask and then oil was added. Before combining with the alcohol-catalyst mixture, the palm oil was subjected to heat at 45°C. After addition of oil, the mechanism maintains air tightness to prevent alcohol loss.

To speed up the process, the reaction mixture was held slightly below the alcohol's boiling point and the reaction proceeded. On the water heater at a temperature of 50-60 °C constantly, the reaction was maintained. Response time normally ranges from one to eight hours. After the reaction was over, glycerin and biodiesel were obtained as the two main byproducts. The biodiesel was ready for further processing when the glycerin was separated by gravity as the glycerin was much denser than the biodiesel. The glycerin removal procedures were typically carried out using centrifugation or gravity settling. The 3% to 6% methanol that remained in the biodiesel was removed by vaporization. Once it was removed, the biodiesel must be washed to remove further residues of glycerin, methanol, soaps, or catalyst. This was accomplished using liquid-liquid extraction, which involved combining water and biodiesel while slowly stirring. The soap was then separated using gravity. It took three to four cycles of washing before the wash water stopped picking up soap. By heating the cleaned biodiesel at 100°C for 10 minutes, any remaining water was eliminated. Finally, 100% pure biodiesel that could be used was obtained.

2.1. Coffea Arabica L natural antioxidant extraction

Use of antioxidant additive in biofuel becomes imperative to achieve oxidation reduction. Antioxidant assists to a greater extent in deterring the free radical formation and intrudes in the oxidation process. The antioxidant additives in general are got both from natural and synthetic process. Tertiary butyl hydroquinone, butylated hrdroxyanisole, butylated hydroxytotulene are a few synthetically obtainable additives. But they pose carcinogenic effect if mixed with air as they are obtained from fossil sources. Therefore opting for a natural antioxidant additive that should be non-toxic, economically viable and renewable is important.

Figure 2. Methyl ester of palm oil production

Antioxidant used for this research work is obtained from the leaves of popular plant variety, Coffea Arabica L. For the synthesis of Coffea Arabica L antioxidant, fresh green leaves of coffee plant are got from Yercaud, a hill station in Tamilnadu. First moisture content in the coffee leaves is completely removed. A 50g of dried leaves is ground to a fine powder of approximately 1.0 mm. The ground powder is used for additive solution extraction in the Soxhlet apparatus using 500 ml ethanol as solvent. The process was continued for two hours to obtain the coffee leaf additive.

3. Materials and methods

3.1. Coffea Arabica antioxidant and diesel blend preparation

Palm seed biodiesel blend of POME20 (80% of diesel fuel with 20% biodiesel) with no antioxidant additive, POME20 with 500 ppm Coffea Arabica antioxidant (PSBC500), POME20 with 1000 ppm Coffea Arabica antioxidant (PSBC1000), POME20 with 1500 ppm Coffea Arabica antioxidant (PSBC1500) and POME20 with 2000 ppm (PSBC2000). The various physico-chemical properties of the test blends is indicated in the Table 2. These test blends were prepared and tested in rancimat apparatus setup for assessing the oxidation stability.

Table 2. Physico-chemical properties of the test blends

Type of Engine	Kirloskar TV-1
Intake Charge	Naturally Aspirated
Power	5.2 kW
Speed	1500 rpm
Compression Ratio	17.5 : 1
Injection pressure	220 kg/cm^2
Injection Timing	23° bTDC

3.2. Experimental setup

The test involved the Kirloskar TV-1, a vertical cylinder, four-stroke, single-cylinder, direct injection, water-cooled, constant speed engine. The experimental setup is depicted in Figure 3 and the technical specifications for the engine are listed in Table 3. To apply various loads, the engine was connected to an eddy current dynamometer. The combustion chamber pressure is measured using a piezoelectric pressure transducer made by AVL that is installed into the cylinder head and has a sensitivity of 16:11 pc/bar. The proportional electric signals are created from the charge yield produced by the piezoelectric transducer by an AVL 3057 charge amplifier. In order to gather data on combustion parameters such heat release rate, incylinder pressure, and cyclic changes, a personal computer (PC) was interfaced with an AVL 619 indimeter hardware and medium-software version 2.2 data collecting system.

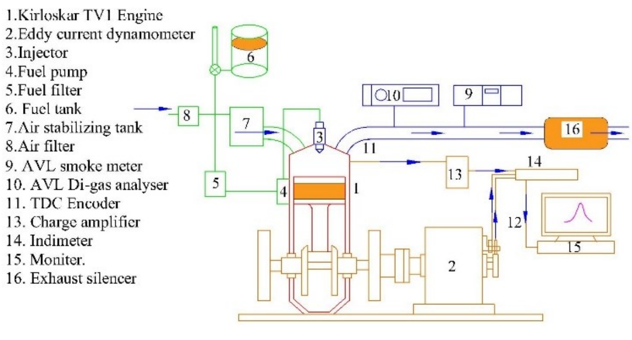

Figure 3. Experimental setup

Table 3. Specification of the test engine

Type of Engine	Kirloskar TV-1
Intake Charge	Naturally Aspirated
Power	5.2 kW
Speed	1500 rpm
Compression ratio	17.5 : 1
Injection pressure	220 kg/cm2
Injection Timing	23° bTDC

The built-in magnetic pick-up sensor is attached to a frequency metre and used to detect engine speed. The emissions such as Hydrocarbon (HC), Carbon monoxide (CO), and nitrogen oxide (NOx) are observed using an AVL

444 Di gas analyzer. Using an AVL 413 smoke meter, smoke density is measured. Using a k-type thermocouple, the exhaust gas temperature was monitored.

4. Engine test

In this work, the engine was tested with antioxidant derived from Coffea Arabica L in various ppm's with POME20 blend. All measurements were done at least three times while the engine was kept running at a consistent speed. Finally, the calculation was made by taking the median value of the three readings.

4.1. Error analysis

Choice of the equipment, its condition, environment, calibration, observation, reading, and test preparation will normally lead to uncertainties and errors in the experiments. The uncertainty analysis is required in order to demonstrate the experiment correctness. The percentage uncertainties of several instruments were used to compute the various characteristics, such as brake thermal efficiency, total fuel consumption, specific fuel consumption, and brake power and it was observed that the overall experiment's level of uncertainty is 2.27%.

5. Results and discussion

5.1. Performance parameters

5.1.1. Brake specific fuel consumption (BSFC)

The BSFC changes with regard to brake power (BP) for plain DF, POME 20, and POME 20 infused with an antioxidant ingredient (Coffea Arabica) in different quantities are shown in Figure 4. The mass flow rate of fuel to the engine's BP output is measured as BSFC. According to the experimental study, the BSFC for the blends of DF, POME 20, PSBC500, PSBC1000, PSBC1500, and PSBC2000 at full load conditions are, respectively, 0.419 kg/kWhr, 0.432 kg/kWhr, 0.429 kg/kWhr, 0.425 kg/kWhr, 0.423 kg/kWhr and 0.421 kg/kWhr. In comparison to POME20, PSBC mixes had BSFC reductions of 0.73%, 1.62%, 2.08%, and 2.55%, respectively. The graph showed that, for all test mixes, BSFC declined as the load condition increased. Due to a smaller percentage of heat energy lost at greater loads and a lower temperature gradient in the warmed-up state, this is less than the percentage increase in braking power output. The inclusion of Coffea Arabica antioxidant ingredient to the POME 20 blend, which enhances combustion by oxidizing the unburned hydrocarbon inside the combustion chamber, is what caused the BSFC drop. The inclusion of antioxidant also results in improved surface area to volume ratio. This improves fuel atomization and quickens the evaporation process in the combustion chamber.

5.1.2. Brake thermal efficiency (BTE)

The variance in BTE for several test blends with regard to BP is displayed in Figure 5. The conversion of fuel energy into mechanical output, a drop in heat loss, and an escalation in power were considered the three main components of BTE. The trials showed unequivocally that for all test mixes, BTE rose as engine load increased. The primary reasons for the rise in BTE are a consistent decrease in heat loss and a rise in power generated when the load is at its maximum. The maximum BTE for plain diesel fuel was 29.2%, but the maximum BTEs for POME 20, PSBC500, PSBC 1000, PSBC1500, and PSBC 2000 were 27.2%, 27.6%, 27.0%, 28.4%, and 28.9%, respectively. Overall, the POME20 blend additive test fuels with the Coffea Arabica antioxidant component almost performed as same that of plain diesel fuel.

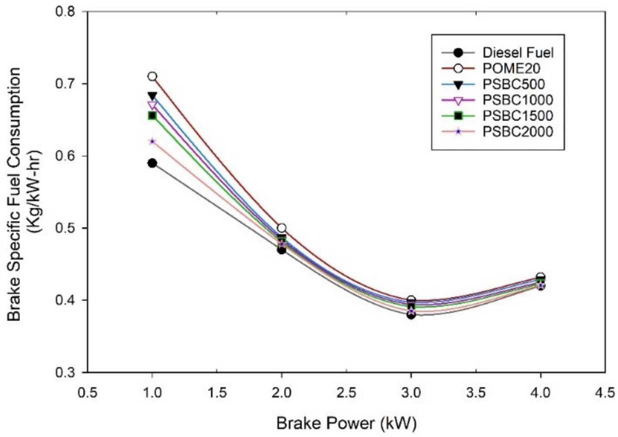

Figure 4. BP vs BSFC for DF and various blends of POME 20 with antioxidant

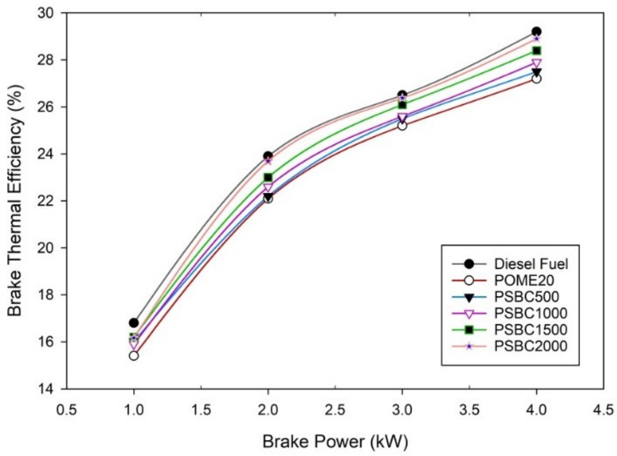

Figure 5. BP vs BTE for DF and various blends of POME 20 with antioxidant

5.2. Emission parameters

5.2.1. Smoke density (SD)

The smoke density for different test blends at different engine brake power levels is displayed in Figure 6. The findings demonstrated that the smoke emissions of all test blends increased as engine loads increased. Smoke emissions increased because there was extra fuel during the peak load time that could not be completely burned off. Fuel additives containing oxygenated materials can be used to remedy this issue. The smoke density values at full load for plain DF, POME20, PSBC500, PSBC1000, PSBC1500, and PSBC2000 were 46 HSU, 49 HSU, 45 HSU, 42 HSU, 39 HSU, and 36 HSU, respectively. The experimental analysis unequivocally demonstrates that, in comparison to the plain diesel fuel performance, smoke emission significantly decreases when the Coffea Arabica antioxidant mixed with POME20 blend. The test blends PSBC500, PSBC1000, PSBC1500, and PSBC2000 exhibit significantly lower smoke densities (2.17%, 8.69%, 15.22% and 21.74%, respectively) when compared to plain diesel fuel. When Coffea Arabica antioxidant is added to the test fuel blends, oxygen components already present in the blends cause the smoke density to drop. Oxygen molecules prevent the soot from forming nuclei, which accelerates the soot's post-oxidation process. A longer ignition delay leads to improved air-entrainment, which in turn promotes soot reduction for fuel blends containing antioxidants like Coffea Arabica. Coffea Arabica anti-oxidant inclusion increases the availability of oxygen, reduces smoke emissions, and enhances combustion also.

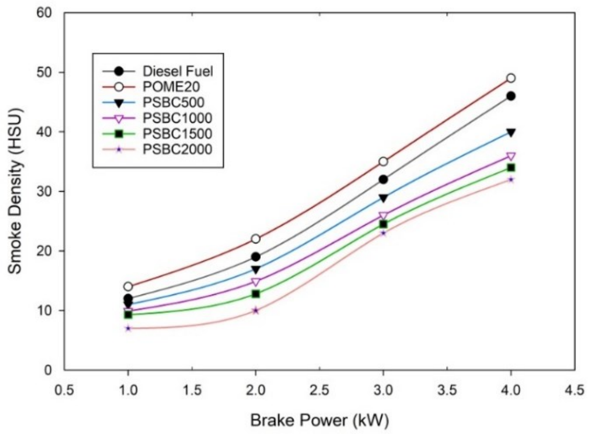

Figure 6. BP vs SD for DF and various blends of POME 20 with antioxidant

5.2.2. Oxides of nitrogen (NOx)

Increased temperatures during combustion promote the production of NOx. Burning biodiesel in the flame to antioxidants is expected to eliminate free radicals' ability to contribute to NOx-producing agents. Brake power has an impact on NOx emissions in test blends, as seen in Figure 7 Comparisons with the plain DF revealed that all of the test blends produced higher NOx emission. The production of NOx emissions was reduced by mixing Coffea Arabica anti-oxidant with the biodiesel. In comparison to POME 20, the PSBC 500, PSBC 1000, PSBC 1500, and PSBC 2000 blends all showed a drop in NOx of around 1.33%, 4.05%, 5.33%, and 6.03% when a Coffea Arabica antioxidant was added to the POME 20 biodiesel mixture. The addition of Coffea Arabica anti-oxidant enhanced the carotenoid's additive and free radical-scavenging activities, resulting in a decrease in adiabatic flame temperature. Coffea Arabica anti-oxidant test mixes lower NOx production by encouraging a lower combustion temperature because of their high latent heat of vaporisation. The NOx emissions of the PSBC 2000 test blends were nearly identical to those of the plain DF.

5.2.3. Carbon monoxide (CO) emission

Figure 8 compares the carbon monoxide graphs for the test mixes to the baseline diesel fuel for different BP values. The most accurate measure of a product's emissions is its CO emissions. Temperature and oxygen saturation level affect CO emissions. In addition, the fuel's physical-chemical properties, a lower flame temperature, a short residence period, and extraordinarily low or high equivalency ratios all contribute to the formation of CO. The carbon, oxygen, and combustion efficiency levels of the fuel determine the amount of CO emissions. The test blends, PSBC 500, PSBC 1000, PSBC 1500, and PSBC 2000, all showed remarkably low CO emission levels against the plain DF and POME 20 blend performance. Significantly less CO was released after antioxidants from Coffea Arabica were added. When comparing PSBC 2000 to POME 20 and plain DF, the CO emission reductions were 18.19% and 12.45%, respectively. Coffea Arabica anti-oxidant's lower C/H ratio is the reason for this.

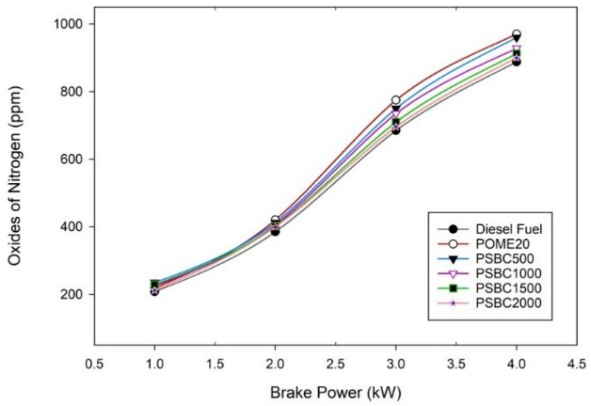

Figure 7. BP vs NOx for DF and various blends of POME 20 with antioxidant

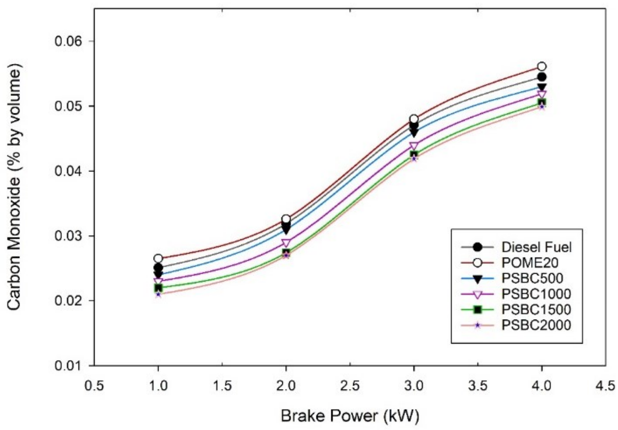

Figure 8. BP vs CO for DF and various blends of POME 20 with antioxidant

5.2.4. Unburned hydro carbon (UBHC) emission

For each of the test blends used in the experiment, Figure 9 shows the relationship between BP and unburned hydrocarbon (UBHC) emissions. When fuel and air are combined in excess of the flammability limits, incomplete combustion is assumed to be the main source of UBHC emissions. UBHC emissions are affected by the gasoline's quality, the engine's operating environment, and the fuel spray's properties. Moreover, insufficient combustion, heat loss to cold areas, flame quenching, and slower oxidation of excessively rich or poor fuel air ratios inside the combustion chamber all contribute to the formation of UBHC. Compared to the other test blends, which had reductions of 9.2%, 11.7%, 10.8%, and 13.5% for PSBC 500, PSBC 1000, PSBC 1500, and PSBC 2000 blends, respectively, the UBHC of the POME 20 was higher at 47 ppm. The UBHC was lower than both the POME 20 and the plain DF for the Coffea Arabica anti-oxidant infused blends, PSBC 500, PSBC 1000, PSBC 1500, and PSBC 2000 blends. Because antioxidant extract from Coffea Arabica was added, the test blends had higher oxygen content. This improved combustion led to a decrease in UBHC.

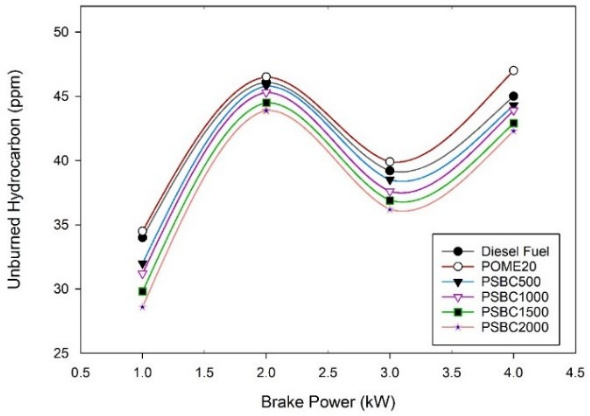

Figure 9. BP vs UBHC for DF and various blends of POME 20 with antioxidant

5.3. Combustion analysis

5.3.1. Heat release rate (HRR)

The HRR change of POME 20 and its Coffea Arabica anti-oxidant's, as well as plain DF, are shown in Figure 10. The test mixes displayed higher HRR than the DF. The graph shows that only during the premixed combustion phase does the maximum heat output occur. The HRR of the blends PSBC 500, PSBC 1000, PSBC 1500, and PSBC 2000 decreases by 0.87%, 0.92%. 0.97 %, and 1% respectively. At PSBC2000, the heat release performance is nearly identical to that of the POME20 fuel blend. Because the maximum heat addition happens so near to TDC, cycle efficiency rises.

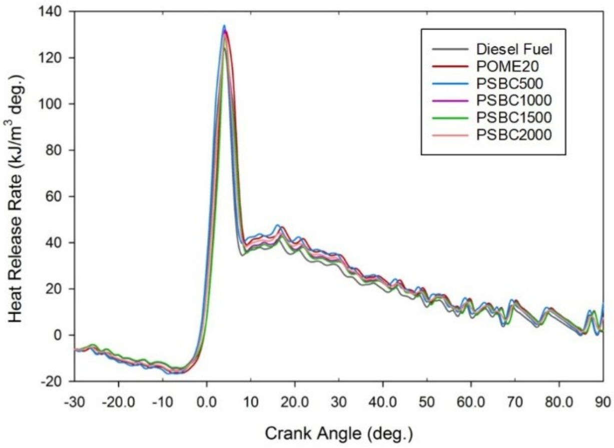

Figure 10. CA vs HRR for DF and various blends of POME 20 with antioxidant

5.3.2. Maximum cylinder pressure (CP)

For plain DF, POME 20, and POME 20 blend with Coffea Arabica anti-oxidant, Figure 11 shows the difference of CP relating to crank angle (CA). The cylinder pressure of POME blends was higher than that of DF. Increased cylinder pressure and better combustion due to extra oxygen present in the POME blends have resulted from the addition of antioxidants. At maximum engine load, the cylinder pressure of POME blends including antioxidant additives, such as PSBC 500, PSBC 1000, PSBC 1500, and PSBC 2000, is increased by 1.022%, 1.027%, 1.035%, and 1.039%, respectively, in comparison to POME 20 mix. Furthermore, it was shown that the peak pressure was generated at crank angles ranging from 5 to 15 degrees after top dead centre by both the POME blends and pure DF. Consequently, the initial burning rate is considerable. Therefore, it was concluded that adding Coffea Arabica anti-oxidants to the POME 20 blend did not cause any problems with the engine's ability to run.

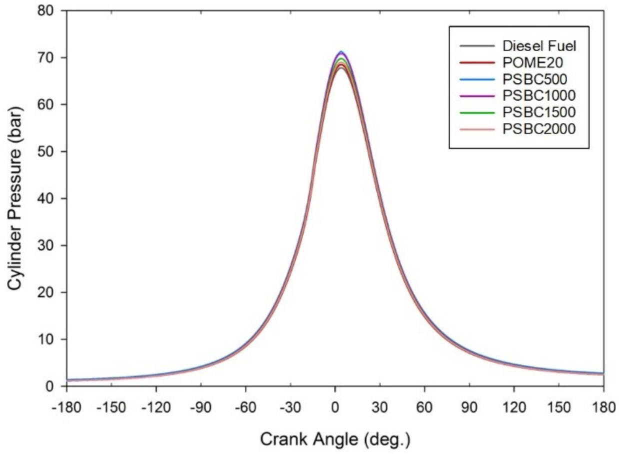

Figure 11. CA vs CP for DF and various blends of POME 20 with antioxidant

6. Conclusion

Engine tests were carried out under varied running situations and the emission performance and combustion characteristics were analysed. The results are listed below.

- BSFC was declined for all test mixes. When compared to POME20, the BSFC was reduced by 0.73%, 1.62%, 2.08%, and 2.55%, for PSBC500, PSBC1000, PSBC1500 and PSBC2000 respectively
- BTEs for POME 20, PSBC500, PSBC 1000, PSBC1500, and PSBC 2000 were 27.2%, 27.6%, 27.0%, 28.4%, and 28.9%, respectively. POME20 blends with Arabica antioxidant component almost performed as same that of plain diesel fuel.
- The smoke emission significantly decreased for the Coffea Arabica antioxidant mixed with POME20 blend. The test blend PSBC2000 exhibits significantly lower smoke density by 26.53% and 21.74% as compared to POME 20 and plain DF respectively.
- The addition of Coffea Arabica anti-oxidant enhanced the carotenoid's additive and free radical-scavenging activities, resulting in a decrease in adiabatic flame temperature. Consequently, the NOx emission of the PSBC 2000 test blends was nearly identical to that of the plain DF and it is also observed that 1.33% to 6.03% reduction as compared to PSBC blends with POME20.
- CO was also less for all Coffea Arabica antioxidants mixed blends. When comparing PSBC 2000 to POME 20 and plain DF, the CO emission reductions were 18.19% and 12.45%, respectively.
- The UBHC was lower for all Coffea Arabica anti-oxidant infused blends. Because anti-oxidant extract from Coffea Arabica was added, the test blends had higher

oxygen content. This improved combustion led to a decrease in UBHC.

- The HRR of the blends PSBC 500, PSBC 1000, PSBC 1500, and PSBC 2000 were also decreased by 0.87%, 0.92%. 0.97 % and 1% respectively.
- Adding Coffea Arabica anti-oxidants to the POME 20 blend did not cause any problems with the engine operation to run.

Therefor to conclude, among the Coffea Arabica anti-oxidant infused blends, PSBC 2000 was found to have closer tolerant properties as that of plain diesel fuel.

Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

Data availability statement

The raw/processed data required to reproduce these findings cannot be shared

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