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Graphene Oxide Nanoparticle Blended Tamanu Methyl Ester as a Promising Alternative Fuel for Unmodified Compression Ignition Engine

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Abstract: This study evaluates the performance and emission characteristics of Tamanu Methyl Ester (TME) biodiesel blended with Graphene Oxide (GO) nano additives at concentrations of 25, 50, and 75 ppm. Engine tests were conducted on a standard compression ignition engine under varying load conditions. Results indicate that the TME20 blend with 50 ppm GO (TME20+GO50) demonstrated optimal performance, achieving a 4.8% improvement in brake thermal efficiency and a 12.6% reduction in smoke opacity compared to diesel. The inclusion of GO enhanced combustion efficiency through improved heat transfer and catalytic activity, resulting in reduced CO and HC emissions. Notably, NOx emissions decreased by 10.19%, attributed to GO's oxygen vacancies and its role in moderating peak combustion temperatures. This study identifies TME20+GO50 as a viable and sustainable alternative to conventional diesel, offering enhanced engine performance and cleaner emissions. Future research should focus on the long-term operational effects of GO nano additives to further optimize their potential.

Keywords: Nanoparticle, NOx Reduction, Tamanu Methyl Ester, Surface area

1. Introduction

As compared to other industries, the automotive industry is one of the most energy-intensive in the world. It is estimated that approximately 90% of all vehicles on the planet are powered by fossil fuels, which cannot be sustained for an extended period. According to industry experts, the world's oil reserves are depleting, and the price of fuel will rise as a result in the coming year. That being said, the world's energy demands continue to rise daily, and therefore, the prominent way to meet them is for us to turn our attention to alternative forms of energy production [1]. It is a great idea to replace fossil fuels with fuel derived from seeds and fats derived from plants and animals, not only because biodiesel has several advantageous characteristics, such as high performance, low emissions, and widespread availability, but also because it is renewable and environmentally friendly [2]. Several characteristics distinguish biodiesel from regular gasoline, including its biodegradability, higher lubrication, which is beneficial to the engine, renewable nature, lower emissions, including greenhouse gases, improved engine efficiency, and so on. Because of a variety of factors, biodiesel is a viable alternative fuel for diesel engines that can be used in vehicles. Additionally, biodiesel has a high viscosity, which can be a problem in colder temperatures, and it is also highly susceptible to oxidation, which makes it an unsuitable fuel for a variety of applications [3]. According to the available literature, the influence of tertiary-based additives and oxygenated mixed fuels results in a higher range of fuel consumption and a reduction in brake power over a wide range of driving conditions. It is also believed that the nano additive will aid in the achievement of increased brake power during the combustion process [4]. As a result of their significant advantages, nanoparticles are quite often referred to as fuel catalysts. These advantages include increased energy density, improved combustion (by reducing the ignition delay), and reduced engine tailpipe emissions, among other things. Researchers have discovered that including nanoparticles in biodiesel blends results in a higher surface area-to-volume ratio, which results in increased oxidation and evolution of the fuel. Improvements in flash points and kinematic viscosity have been achieved through the use of nano-added compounds in both neat diesel and blended biodiesel [5].

It is often recognized that the nanoparticles combined with biodiesel display a greater Exhaust Gas Temperature (EGT) than other biodiesel blends due to the potential of nanoparticles to boost combustion and, consequently, the brake thermal efficiency (BTE) of the engines [6]. As a result of their increased surface area-to-volume ratio and enhanced catalytic action, nano additives contribute to the reduction of automotive emissions while enhancing combustion. HC and CO emissions are reduced under evaporation circumstances; however, MWCNT reduces NOx, CO, and smoke emissions and improves engine performance [7]. CNTs were added at a concentration of 50 ppm to all gasoline mixtures. The studies were performed by altering the engine's load. The results indicated that the performance characteristics of the B15C50 fuel blend, including power, torque, brake thermal efficiency (BTE), and Specific Fuel Consumption (SFC), are superior to those of other fuel blends and pure diesel [8]. Compared to widely used nano additives such as Al_2O_3 and TiO_2, GO's higher surface-to-volume ratio and oxygen vacancy density provide superior catalytic efficiency, enhancing combustion and reducing emissions more effectively. For instance, TiO_2-based additives excel in reducing particulate matter but are less effective in NOx mitigation due to their limited thermal conductivity. Al_2O_3, while cost-effective, lacks the multifunctional catalytic properties of GO. GO is more expensive in the initial stages, but its dual benefit of increasing combustion efficiency and reducing emissions balances that out by saving on total fuel consumption and cost of emission control [9].

TME biodiesel, developed from the seeds of the Calophyllum inophyllum tree, is renewable and environmentally friendly compared to conventional diesel. The high oxygen content in this fuel results in improved combustion; hence, its biodegradability contributes to reduced environmental impact [10]. Nevertheless, there are some disadvantages of TME biodiesel, including lower calorific value and higher NOx emissions compared to fossil diesel. Advanced additives like GO can be incorporated into the fuel to overcome the aforesaid limitations by way of improved combustion and emission characteristics. The purpose of this study is to ascertain how GO nano additions affect the emission characteristics and performance of TME biodiesel blends in CI engines. The impacts of GO on specific fuel consumption, thermal efficiency, and combustion efficiency are examined in this study, as is its contribution to the reduction of hazardous emissions such CO, NOx, unburned HC (UHC), and smoke opacity. The study also attempts to identify the ideal GO nano-additives concentration that achieves a compromise between improved performance and reduced emissions. Significant improvements in combustion and emission characteristics are predicted when GO nano-additives are added to TME biodiesel blends.

2. Materials and Methods

While the sample was undergoing the FT-IR analysis, it was inspected with a Shimadzu IR Tracer 100 device. Within the wavenumber range of 500 to 4000 cm-1, the liquid phase sample reached the highest peaks. The range was covered by the sample. The FTIR spectroscopy was carried out at the SRM Institute of Science and Technology, Chennai. Those functional groups that are present in the liquid phase sample can be recognized in the spectrum by their high peaks. The components of the sample found in the liquid phase are as follows: alkenes, alkanes, alkyls, acids, and alcohols. In addition to that, it has alkynes.

Figure 1 presents the findings of the FT-IR analysis that was conducted on TME. According to the data from the spectrum, the reaction results in a typical mixture of methyl esters being produced. It was discovered that alkyl halides, alkanes, and amines all possess the same configuration for a single bond in their molecules. It was discovered that methyl esters of tamanu include alkyl halides such as chlorine and iodine. Frequencies ranging from 797.58 to 655.81 cm^{-1} are associated with the C-Cl stretch, whereas frequencies ranging from 431.10 to 406.99 cm^{-1} are associated with the C-I stretch. The absorption bands of long-chain fatty acids, which often contain the stretch C-O band, have a particular frequency range that falls between 1220 and 1127.41 cm^{-1}.

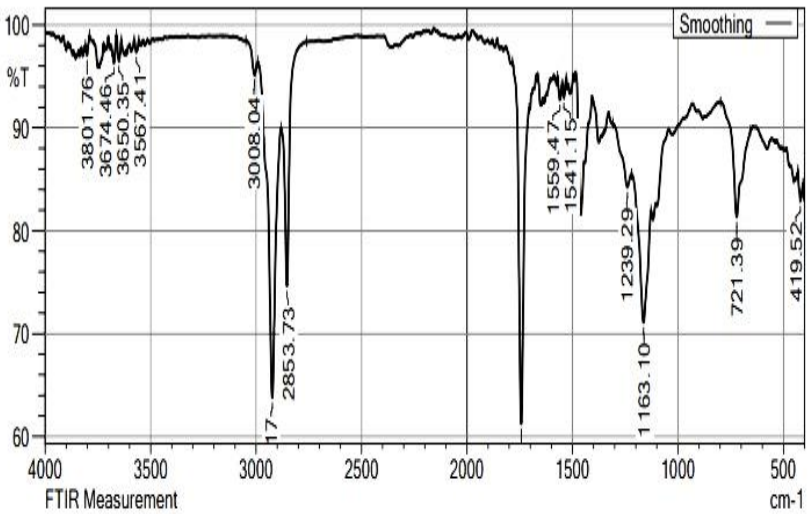

Figure 1. FTIR analysis for Tamanu methyl esters

This portion of the frequency spectrum. The frequency range between 3048.55 and 2991.64 cm^{-1} is the strain absorption band in C-H alkanes. The strain absorption band for N-H amines can be found around 2991.64-2881.70 cm^{-1}. It is a strain absorption band that has a frequency range between 2881.70 and 2761.15 cm-1 and corresponds to the O-H carboxylic acids band. In the carbonyl group of methyl esters, which has a structure consisting of two bonds, the strain absorption band C=O may be found at the following wavelengths: 1546.94-1529.58 cm^{-1}, 1571.05-1551.76 cm^{-1}, and 1784.19-1706.07 cm^{-1}. Analyses of TME biodiesel conducted with FTIR equipment revealed the presence of methyl groups, ester groups, and carbonyl groups, and also aligns with those of findings of Senthilkumar *et al.* [11] on their experiment of FTIR analysis to evaluate the bond structure of tamanu oil.

2.1 GC-MS Analysis

Figure 2 shows the result of GC-MS analysis of TME. GC-MS testing used Shimadzu QP 2010 Plus gas chromatography with a mass spectrometer. Alcohols, esters, fatty acids, and others are measured. The liquid phase sample was dissolved in chloroform, passed through a column, and heated to 50ºC with a hold for 2 min, then 310ºC for 3 min. Helium gas moved the vapor to the gas chromatography column to show the high peaks of the exact components and store the data.

Table 1 lists the compounds' peak values. Most sample high peaks occurred between 2.2 and 36.0 min. GCMS found olefins, paraffin, and naphthenes in the liquid phase sample and is verified valid with reference to study by Susanto *et al.* [12].

2. Experimental Setup

All of the test variables, including engine load, speed, and lubricating oil temperature, were examined and recorded as part of the experimental investigation. The testing procedures were standardized and consistent across all testing sessions, and any deviations from the standard procedures were precisely documented. Each experiment was conducted three times under identical conditions, and results were presented with standard deviations to ensure reliability and reproducibility. Error bars in the graphical data represent the variation, with standard deviations consistently within margin, validating the repeatability of the findings. The reliability and consistency of the engine test findings are ensured by repeatedly conducting the test under identical conditions. On a single-cylinder compression ignition engine, the experiment was conducted. The engine block diagram is depicted in Figure 3. The engine is coupled to a dynamometer operated by an eddy current. A gas analyzer and smoke are utilized to determine the emissions of exhaust gases. In addition, a fuel flow meter is used to monitor fuel consumption, and an exhaust manifold lambda sensor is installed to monitor the air-to-fuel ratio. The data acquisition system is employed to examine the stored signals from the force sensor, thermocouples, fuel flow metre, airflow metre, and speed sensor. The engine's cylinder pressure is determined using a piezoelectric pressure sensor.

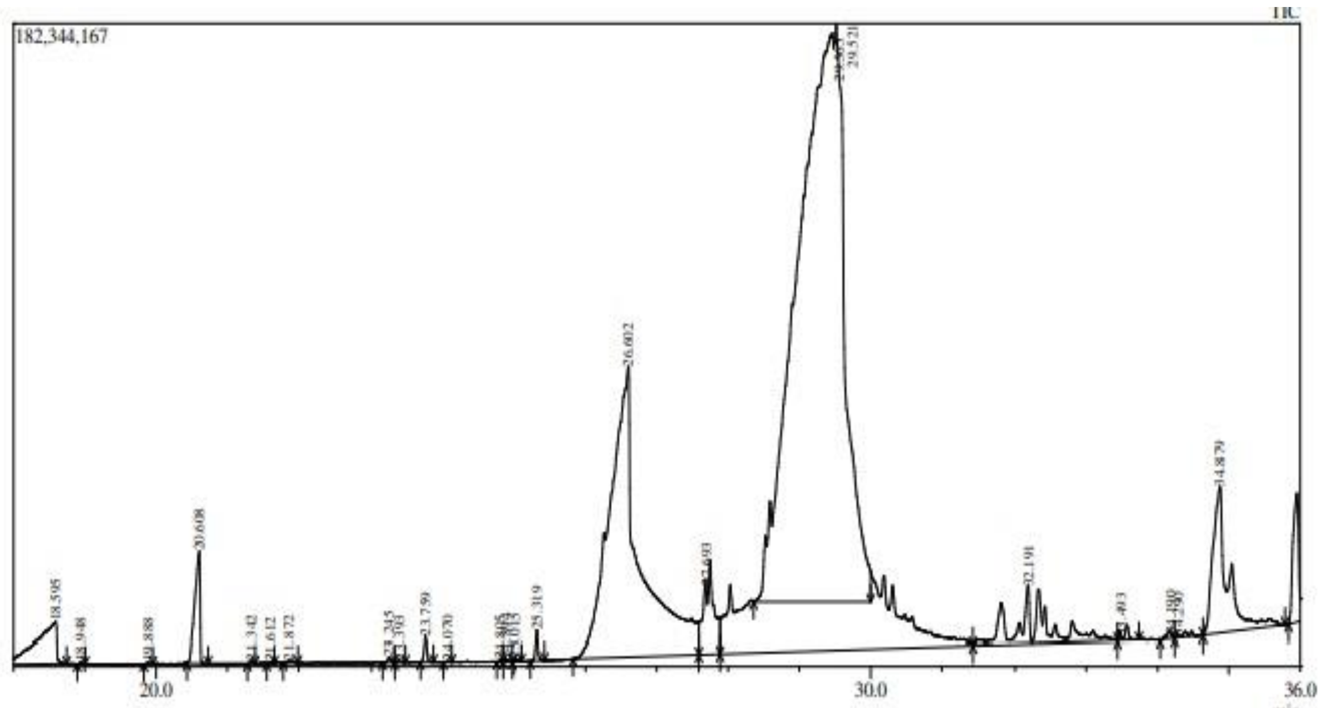

Figure 2. GC-MS analysis for Tamanu methyl esters.

Table 1. Chemical composition of Tamanu methyl esters

S.No.	Peak No.	Run time	A/H	Chemical Name	Chemical Structure
1	5	4.385	3.42	HEXANAL	$C_6H_{12}0$
2	9	6.909	2.05	HEXANOIC ACID, METHYL ESTER	$C_7H_{14}O_2$
3	14	7.847	3.62	2-HEXENOIC ACID, METHYL ESTER	$C_7H_{12}O_2$
4	19	8.520	2.91	DECANE	$C_{10}H_{22}$
5	27	10.767	2.14	TETRADECANE	$C_{14}H_{30}$
6	29	11.158	2.78	1-DODECYNE	$C_{12}H_{22}$
7	40	13.449	2.27	NONANOIC ACID, METHYL ESTER	$C_{10}H_{20}O_2$
8	45	14.272	2.41	OCTADEC-9-EN-1-AL DIMETHYL ACETAL	$C_{22}H_{42}O_2$
9	61	16.821	3.22	2-PROPENOIC ACID, 3-PHENYL-, METHYL	$C_{10}H_{10}O_2$
10	65	17.761	2.46	OCTANEDIOIC ACID, DIMETHYL ESTER	$C_{10}H_{18}O_4$
11	69	18.608	2.59	TETRADECANE	$C_{14}H_{30}$
12	72	19.532	2.55	NONANEDIOIC ACID, DIMETHYL ESTER	$C_{11}H_{20}O_4$
13	81	21.197	3.02	DECANEDIOIC ACID, DIMETHYL ESTER	$C_{12}H_{22}O_4$
14	86	22.337	2.33	PENTADECANOIC ACID, METHYL ESTER	$C_{16}H_{32}O_2$
15	95	25.578	13.77	HEXADECANOIC ACID, METHYL ESTER	$C_{17}H_{34}O_2$
16	100	26.676	3.76	OCTADECANOIC ACID, METHYL ESTER	$C_{19}H_{38}O_2$
17	113	30.518	5.14	TRIACONTANOIC ACID, METHYL ESTER	$C_{31}H_{62}O_2$
18	115	31.042	3.19	ASPIDOSPERMIDIN-17-OL, 1-ACETYL-16	$C_{22}H_{24}N_2O_2$
19	122	32.230	5.18	2-METHYL-Z,Z-3,13-OCTADECADIENOL	$C_{19}H_{34}O$
20	125	32.743	5.42	HEPTACOSANOIC ACID, METHYL ESTER	$C_{29}H_{58}O_2$
21	135	34.826	10.74	9-OCTADECENOIC ACID, 1,2,3-PROPANETRIYL ESTER	$C_{57}H_{104}O_6$
22	136	34.964	6.76	OCTADECANOIC ACID, 2,3-DIHYDROXY PROPYL ESTER	$C_{21}H_{42}O_4$

3. Result and Discussion

The utilization of TME and its blends has the potential to be used as an alternate fuel source for CI engines. According to the findings, the TME20 blend has remarkable emissions and reasonable efficiency when compared to other TME-diesel blends. As a result, the TME20 blend produced minimal HC and CO emissions and had a negative influence on NOx emissions. To reduce the emission of NOx, TME20 was doped into the nano additive. In this study, GO was chosen as a nano additive blend with TME20, and it was compared with pure TME and diesel in a CI engine to assess the combustion, performance, and emissions characteristics.

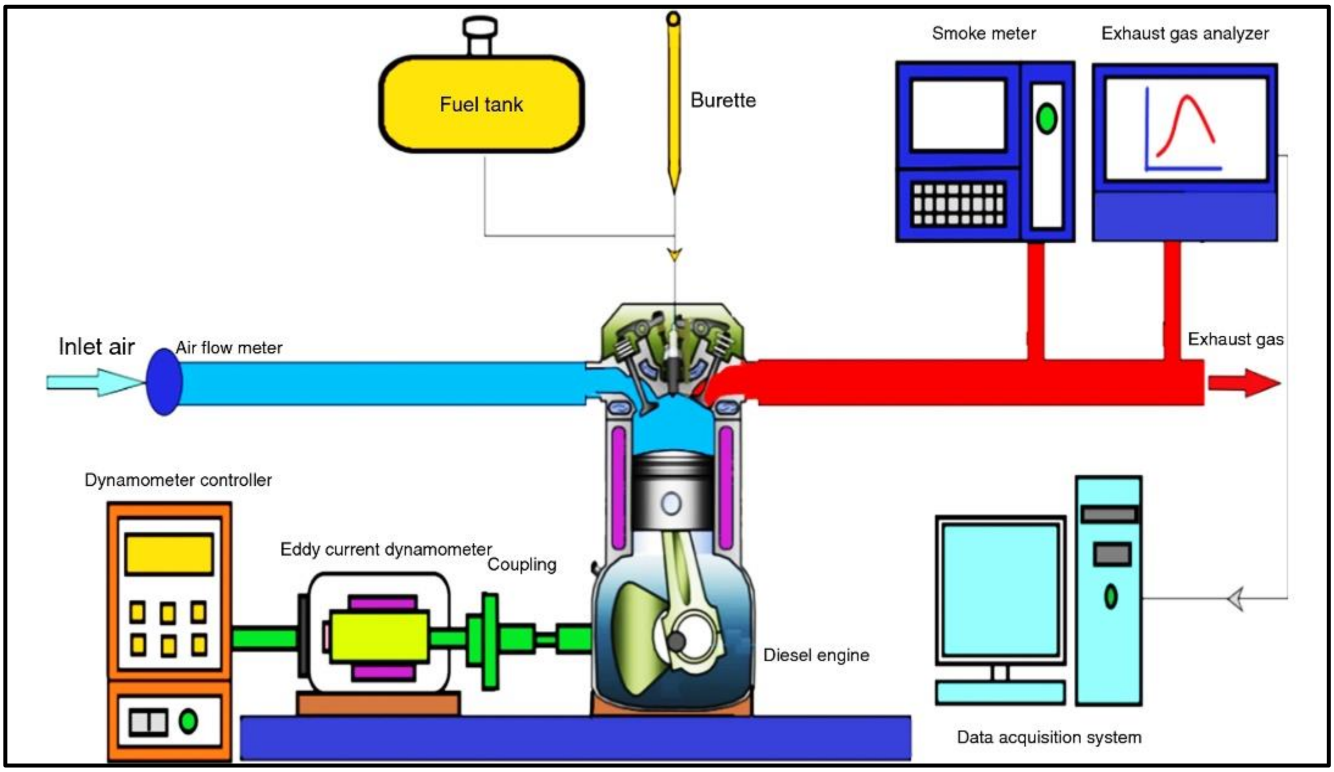

Figure 3. Schematic diagram of engine setup

3.1. Emission characteristics

3.1.1. CO emission

Inadequate fuel atomization and incomplete combustion result in CO emissions. The CO formation according to varying engine loads and tested fuels is shown in Figure 4. Across all tested fuels, CO emission rises as the engine load rises to 5.65 kW. Compared to diesel and TME20 blend, neat TME showed decreased CO emission. For blends of TME20 with GO concentrations of 25, 50, and 75 ppm, the resulting CO emission was 0.169, 0.165, and 0.167% vol., respectively. Complete combustion and the enriched oxygen received from the nano additives resulted in a minor reduction in CO emissions for all nano-TME blends compared to the other test fuel. TME20 with nano additive concentrations of 25, 50, and 75 ppm resulted in 12.4%, 14.5%, and 13.4% greater CO emissions from diesel, respectively, at full load. All fuel blends produced more CO emissions than TME20+GO50ppm at peak load, while TME20+GO75ppm had a nominal decrement of about 1.5%. This could be the cause of the GO nano additive's larger surface-to-volume ratio and more reactive nature, which lead to appropriate atomization and a faster combustion rate that minimizes the production of CO emissions. Furthermore, GO nano additives had a greater oxygen supply, which improves the test fuel's ignition and rate of fuel evaporation.

This enhanced oxygen supply, coupled with the catalytic properties of GO, further promotes the oxidation of residual CO and CO_2. The oxygen vacancies in GO act as active sites, improving the availability of oxygen during combustion and ensuring more complete oxidation of fuel molecules [13]. Additionally, the superior thermal conductivity of GO contributes to a uniform temperature distribution within the combustion chamber, minimizing areas of incomplete combustion that could lead to higher CO emissions [14]. Experimental results confirm these benefits, with the TME20+GO50ppm blend demonstrating a 14.5% reduction in CO emissions compared to diesel, underscoring the catalytic efficacy of GO in reducing harmful pollutants.

3.1.2 HC emission

The generation of UHC emissions is shown in Figure 5, for various engine loads and fuel types. During inadequate combustion, fuel particles are left behind in the exhaust and crankcase, resulting in UHC emissions. It's also because of the poor HC oxidation process caused by the decreased cylinder temperature. At peak load, all the fuel showed higher HC emissions than mid-load and initial load conditions. Diesel at normal mode revealed higher HC emissions than TME and TME with nano additive due to its poor oxygen capacity. Nano additives blended TME20 had marginal decrement with diesel and pure TME. For blends of TME20 with GO concentrations of 25, 50, and 75 ppm, the resulting HC emission was 91, 88 and 89 ppm, respectively. This could be the reason that GO are capable of releasing more amount of oxygen during combustion which reacts with fuel particles thereby improving the oxidation process.

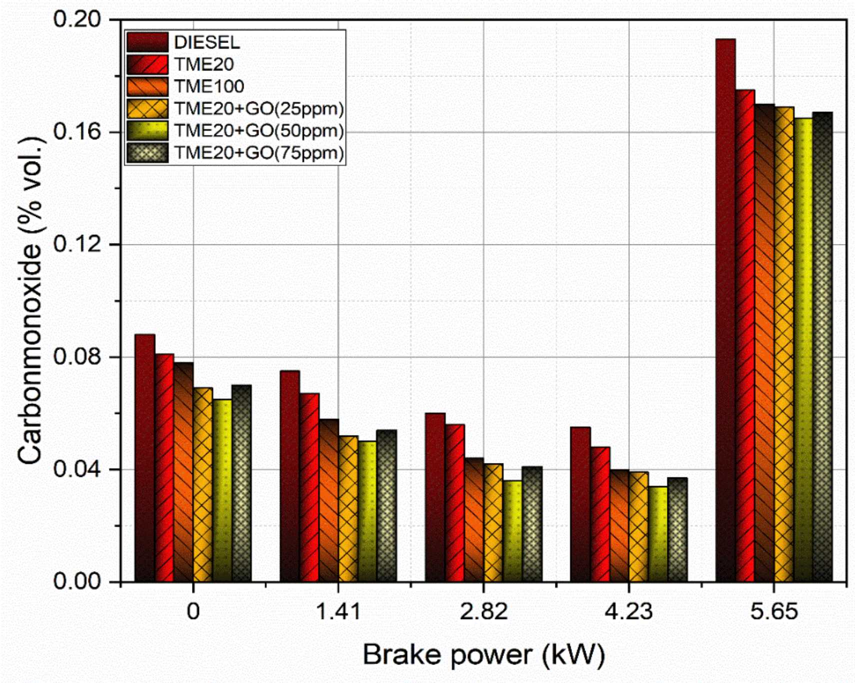

Figure 4. Variation of CO emissions across engine loads for tested fuel blends. GO-doped TME blends exhibited lower CO emissions due to enhanced catalytic oxidation facilitated by oxygen vacancies in GO

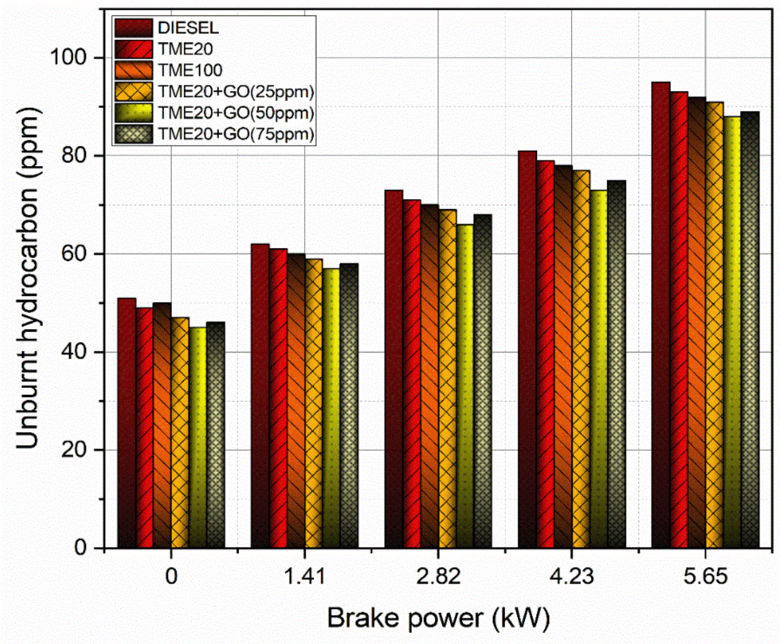

Figure 5. HC emissions for different fuel blends under varying loads. The addition of GO nano additives to TME20 resulted in reduced HC emissions, attributed to improved oxidation and complete combustion processes

Due to the higher surface-to-volume ratio, the relationship between the GO with fuel was increased and the HC emissions were reduced [15]. In particular, the TME20+GO50ppm achieved the lowest level of HC emission at rated BP conditions. In addition, there is improvement in ignition delay, spray penetration and evaporation characteristics. The GO50ppm blend shows extended results in terms of HC reduction due to improved heat transfer characteristics within the fuel's inner layer thereby increasing the combustion.

3.1.3. NOx emission

The variation of NOx emission with brake power for different fuels with and without blended nano additive.

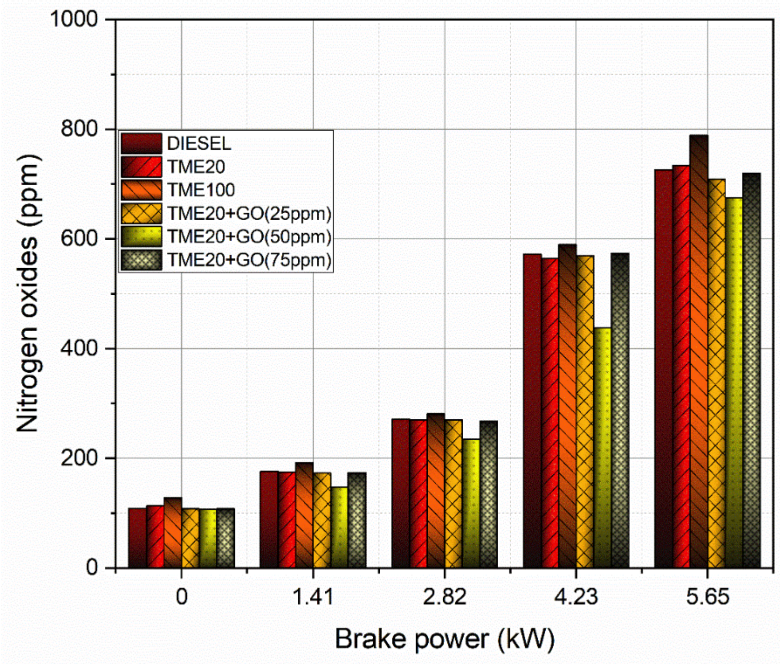

Figure 6. NOx emission trends with engine load for tested fuel blends. GO-doped TME blends showed significant reductions in NOx emissions due to lower peak combustion temperatures and enhanced heat distribution

As shown in Figure 6, there is a proportional increase in NOx emission for the loads for all fuels. NOx emission was produced by the highest temperature combustion process to produce NOx. BP when increasing NOx emission also increases due to elevated combustion temperature. The value of NOx emission from TME was high compared to diesel. This increment of NOx emission is due to the inherent O_2 content in TME and the high gas temperature of biodiesel. At a peak load, the NOx of diesel, TME and TME20 are 726, 789 and 734 ppm respectively. The resulting NOx emission was 709, 675 and 720 ppm for blends of TME20 with 25, 50, and 75 ppm of GO, respectively. There is a modest reduction in NOx emissions when using the TME20+50ppm blend compared to the other fuel combinations.

This reduction can be attributed to several mechanisms introduced by GO nano-additives. The high thermal conductivity of GO facilitates efficient heat dissipation within the combustion chamber, lowering peak in-cylinder temperatures, critical to NOx formation. Furthermore, the oxygen vacancies in GO actively scavenge free oxygen radicals, limiting their availability to react with nitrogen and form NOx compounds. Another contributing factor is the micro-explosion phenomenon induced by GO, which promotes uniform combustion and prevents the formation of localized high-temperature zones where NOx is likely to form [16]. Experimental observations corroborate these mechanisms, with the TME20+GO50ppm blend achieving a 10.19% reduction in NOx emissions compared to diesel, highlighting GO's role in emission mitigation.

Furthermore, the influence of the in-cylinder temperatures and combustion dynamics by the GO nano additives also makes impact. The catalytic properties of GO, particularly its oxygen vacancies and large surface-to-volume ratio, play a pivotal role in moderating the peak combustion temperature. This is achieved through enhanced thermal conductivity, which facilitates better heat distribution across the combustion chamber, reducing localized high-temperature zones where NOx formation is most pronounced. Additionally, the micro-explosion phenomenon observed with GO-doped biodiesel blends further aids in reducing NOx. This mechanism involves the disintegration of larger fuel droplets into smaller ones, ensuring more uniform combustion and avoiding hot spots. The oxygen vacancies in GO also contribute by scavenging free oxygen atoms during combustion, thus limiting the availability for NOx formation [17]. These combined effects demonstrate the advanced thermophysical and catalytic interactions introduced by GO nanoparticles in the combustion process.

3.1.4. Smoke emission

Figure 7 illustrates the changes in smoke opacity for diesel, pure TME, TME20 and nano TME20 blends in CI engine at all load ranges. As a result, the smoke opacity formation of raw TME is much lower than diesel. It is proof that O2 content in fuel resulted in less smoke than diesel fuel due to the absence of aromatic compounds and lower hydrocarbon ratio. On account of emulsion with optimized nano blend, the obtained result shows a reduction in smoke opacity drastically.

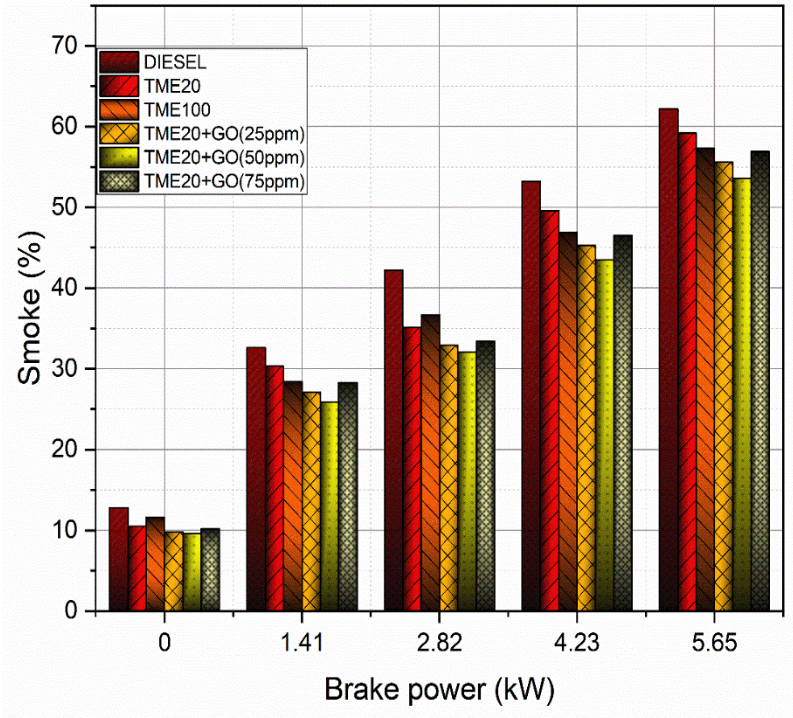

Figure 7. Smoke opacity variation for diesel, TME, and GO-doped TME blends under varying loads. The inclusion of GO nano additives in TME blends significantly reduced smoke opacity, with TME20+GO50 showing the highest improvement, attributed to improved atomization and catalytic oxidation.

In comparison with TME20, it was revealed that the emulsion blends result in lower smoke for the TME blend. Further, graphite oxide nano additive with optimized blend, it was reported that smoke was reduced. Compared with the TME20 blend, it was revealed that the nano blend results are 6.08, 9.4 and 3.8%, with lower smoke for 25ppm, 50ppm and 75ppm respectively. From the results, it was determined that the TME20+GO50ppm blend reported a major drop in smoke owing to the positive effect of droplet diameter size, viscosity and minimal concentration of nano additive. The smoke emission of TME20+GO50ppm blends is closer to that of TME20+75ppm blends and is reduced by 13.8% compared to diesel. This is due to the nano component, which acts as an oxidation catalyst and lowers the ignition temperature for carbon combustion rather than increasing hydrocarbon oxidation. In addition, GO-doped biodiesel blends produce less smoke because of their enhanced catalytic activity and combustion features. This is in line with the phenomenon reported by Murugan *et al.* [18] on their study on doping nanographene oxide in th palm oil methyl ester blend in CI engines.

3.2. Performance Characteristics

3.2.1. Fuel consumption

The SFC of various fuels at different brake powers is illustrated in Figure 8. This experiment involves mixing GO nano additive with B20 biodiesel at various concentrations (25, 50, and 75 ppm). The results show that neat diesel exhibits the lowest SFC among the tested fuels. This is primarily because of biodiesel's inherently lower calorific content, leading to the highest SFC for pure biodiesel. In comparison, TME20, which consists of 20% biodiesel and 80% petroleum diesel, shows better SFC than TME100. This improvement is due to the higher proportion of petroleum diesel in TME20, which increases its overall calorific value. The lower heating value of biodiesel necessitates a larger fuel quantity to achieve the same energy output, thereby increasing SFC. When TME20 is doped with GO nano additives, its SFC is slightly higher than that of neat diesel but shows a significant improvement over TME100. As the concentration of nano additives in the blend increases, the SFC gradually decreases.

This reduction in SFC with increasing GO concentration can be attributed to the enhanced combustion efficiency facilitated by the nano additives. The GO particles accelerate the oxidation during combustion, leading to more efficient fuel utilization and consequently lower SFC. Among the blends, TME20 with 75 ppm of GO demonstrates the best performance, showing a substantial reduction in SFC. This improvement is due to the higher concentration of graphene oxide particles in the fuel with low calorific content, which enhances the catalytic activity during combustion and reduces the overall fuel consumption [11]. Therefore, doping TME20 with GO, particularly at 75 ppm, significantly improves fuel efficiency, making it a viable alternative for reducing SFC in biodiesel blends.

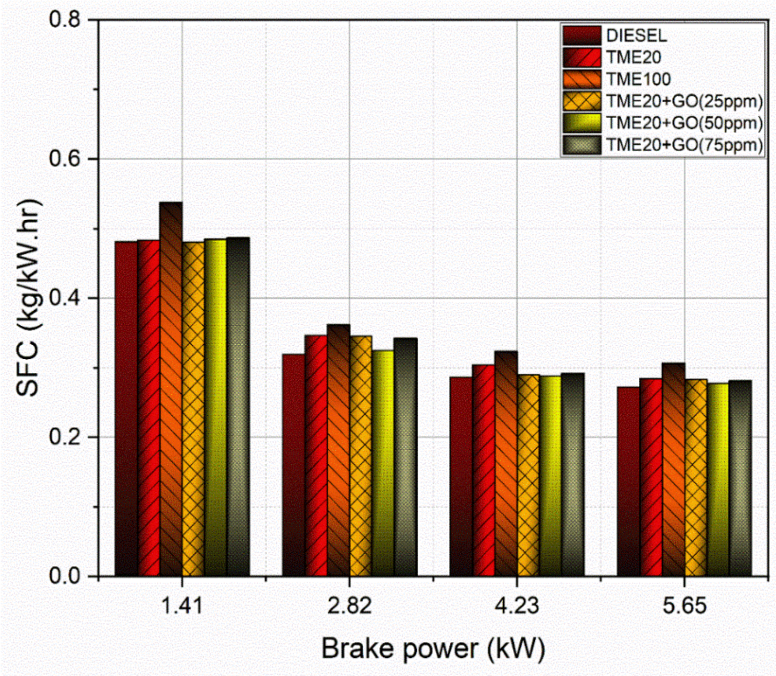

Figure 8. SFC trends under varying brake powers for tested fuel blends. GO-doped TME blends demonstrated reduced SFC due to enhanced combustion efficiency. TME20+GO50 exhibited the lowest SFC among the biodiesel blends, highlighting improved fuel utilization

3.2.2. Thermal efficiency

Figure 9 provides a comparative analysis of the thermal efficiency and brake power of diesel, biodiesel, and nano additive biodiesel mixtures operating on a standard diesel engine. The figure demonstrates that thermal efficiency improves for all fuel types as the load increases. Under optimum load conditions, the BTE of diesel, TME20, and TME100 are observed to be 31.5%, 30.1%, and 27.79%, respectively. Particularly, at different doses, the addition of graphene oxide (GO) nano additions to TME20 greatly increases thermal efficiency. The BTE rate of the TME20+GO25ppm combination is 3.2% more than that of TME20. Additionally, the TME20+GO50ppm blend shows an even better improvement, nearing diesel efficiency levels with a BTE rate 4.8% higher than TME20. A number of parameters related to the GO nano additions are responsible for this increase in thermal efficiency. Because the nano additives have a higher oxygen content, the fuel blend's combustion, atomization, and thermal properties are improved when an ideal ratio of GO is present. In addition to the nanoparticles aiding in the cracking mechanism, this enhanced oxygen availability promotes more thorough combustion, which raises oxidation rates and encourages the combustion of a larger HC percentage [19].

3.3 Combustion Characteristics

3.3.1 Pressure

Figure depicts the crank angle dependence of CP generation for the TME along with nano additive blends with relation to peak load. The fuel tested includes diesel, TME20, TME100 and TME20 blended with concentrations of nano additive at 25 ppm, 50 ppm and 75 ppm respectively, causing the respective values of CP are 64.5, 57.27, 54.75, 58.96, 64.24 and 62.54 bar. The results showed that the CP was higher by 0.85% at TME20+GO, at 50 ppm than that for diesel due to increased oxygen availability for combustion and a progressive combustion as well as improved cetane rating through nano additives. Importantly, both TME20 and the blend of GO nano additives also had a very early onset of combustion in contrast to diesel, under peak load conditions. This premature combustion can be associated with inherent characteristics such as high oxygen content and a higher cetane number of the TME blend [20].

The above results revealed that the evaporation and atomization processes of the TME20 blend were enhanced, and ignition delay was minimized, resulting in higher peak cylinder pressure. Nano additives minimized ignition delays further and accelerated combustion. Especially, nano additives in the TME20 blend were found to exhibit a higher peak cylinder pressure than TME100 and TME20 alone. The addition of GO nano additives resulted in an increase of CP of TME20 by 7.14%, 14.56%, and 12.23% compared with the conventional TME100. Most importantly, at peak load, TME20+GO at 50 ppm showed the highest CP among all the nano additive blends tested. These results prove effective addition of GO to TME as a blend in oxidation and, consequently, enhances peak pressure in the cylinder.

3.3.2 Heat release rate

The HRR of many test gasoline mixes under full load conditions was studied through analysis. Figure 11 contains testing on diesel fuel, TME20, and TME100.

The ignition delay for diesel was substantially increased; a higher HRR (83.67 J/CA) is to be expected. This lag allowed more fuel to form inside the chamber, and thus led to a higher heat release. TME100 however recorded a low HRR of 63.24 J/CA that was due to this faster ignite; there was no enough time for proper heating from this fast ignition.

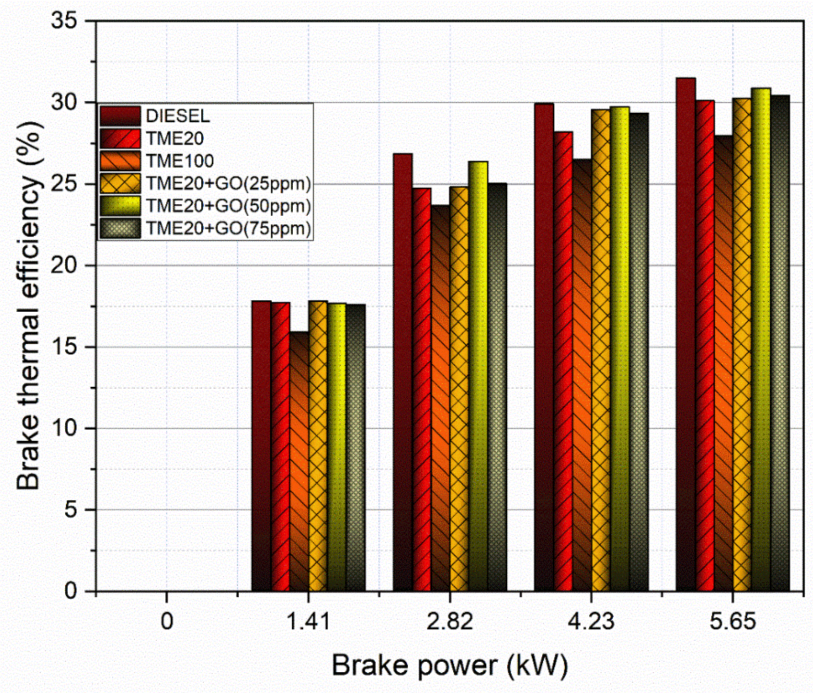

Figure 9. BTE of diesel, biodiesel, and GO-doped TME blends under varying engine loads. TME20+GO50 exhibited the highest thermal efficiency among biodiesel blends, approaching diesel performance levels due to enhanced combustion and atomization properties.

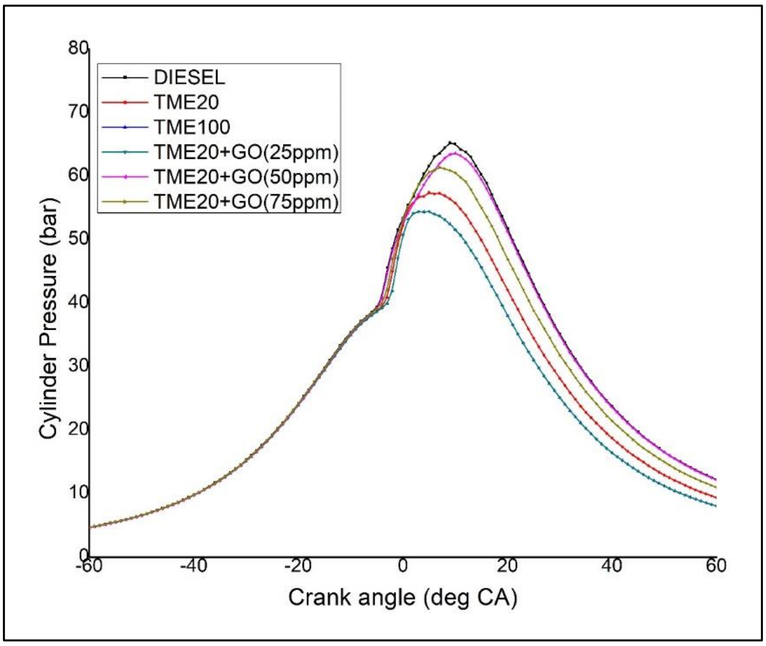

Figure 10. Comparison of cylinder pressure profiles for diesel, TME, and GO-doped TME blends under peak load conditions. The TME20+GO50ppm blend exhibited the highest peak cylinder pressure due to enhanced combustion characteristics, including reduced ignition delay and improved fuel atomization, facilitated by GO nano-additives

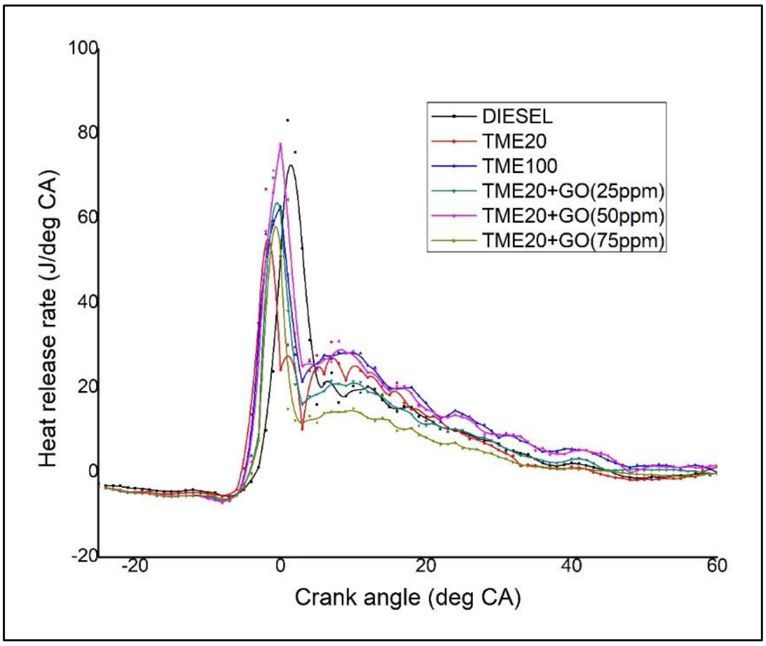

Figure 11. HRR analysis of diesel, TME, and GO-doped TME blends at full load. The blend TME20+GO50ppm showed a much higher HRR value compared with the untreated TME blends due to the faster combustion kinetics and the availability of more oxygen because of GO nano-additives.

ITME20 managed to achieve an HRR of 67.12 J/CA, which will stay in the middle of the two. To the contrary, nano additions made to TME20 was a breakthrough. In the case of TME20, after the addition of these nano additives, there was a significant improvement in HRR. Improvements relative to the untreated TME20 at full load were between 9.5% and 11.42%, depending on the concentration used (25 ppm, 50 ppm, or 75 ppm). It is worth noting that TME20 with 50ppm of nano additives outperformed even diesel fuel by a margin of 6.8% in HRR. It has been surmised that these benefits arise because of the quicker kinetics of combustion contributed by the nano additives and by the oxygen itself in them [21]. At the same time, the addition of TME20 nano exhibited better HRR than that from untreated TME20 at a standard operating state. These increases, varying from 4.45% up to 13.6%, are credited through the function performed by the nano additives that improve in-cylinder pressure and aid effective combustion operations. Adding nano additions to the TME blend was meant to enhance the combustion efficiency. Combustion efficiency resulted in a huge time span of reduction for ignition delay. Improvement in this case is believed to come from the organic oxide layer that envelops the nano additives to slow down the oxidation reaction at lower temperatures [22-25].

4. Conclusion

The current study showed that the incorporation of GO to TME had a substantial enhancement in biodiesel characteristics and engine performance. In the study, TME doped with 25, 50, and 75 ppm GO concentrations was analyzed for engine parameters and conformity to ASTM standards.

- With the inclusion of GO at 25, 50, and 75 ppm, the SFC reduced by 4.5%, 7%, and 12% respectively. However, with parallel comparison with the neat biodiesel, efficiency increased at full loads with increments of 12.22%, 18.32%, and 15.35%. Thermal efficiency has increased in TME20+GO 25 ppm, TME20+GO 50 ppm, and TME20+GO 75 ppm at high loads relative to TME20 by 0.5%, 2.5%, and 1.05% respectively. Thus, the better fuel economy with good combustion outcome is achieved.
- Increases of 2.8%, 10.8%, and 8.4% in the peak cylinder pressures while the associated peak HRRs increased by 4.45%, 13.68%, and 7.35%. The ignition delay was decreased but peak cylinder pressure and HRR increased when GO was added.
- Comparison with diesel reveals that TME with GO nano additives significantly lowers carbon monoxide (CO) and hydrocarbon (HC) emissions. This shows higher and more rapid fuel combustion. CO emissions from diesel were 12.4, 14.5, and 13.4% higher by the addition of GO at 25, 50, and 75 ppm, respectively. The emission of CO into the atmosphere by GO additive in TME20 was very much reduced from 12.1 to 15.2% compared with diesel. At full engine load, the HCs emission reductions were up to 1.2%, 4.9%, and 3.7% compared with pure B100, respectively.

- NOx emissions decreased up to 5.5%, 10.19%, and 3.9% when GO was added but reduced by up to 2.41%, 8.29%, and 3.9% compared with diesel.
- Lesser Smoke emissions by 5.5, 8.6, and 3.5% relative to TME20, whereas smoke opacity lower by 9.70%, 12.6, and 3.53% than diesel. For all TME-GO blends, there are lower smoke opacity values as opposed to neat TME with an optimum at the 50 ppm blend being significant at 12.6 % relative to diesel. Cleaner-burning characteristics would be exhibited coupled with a minimal formation of particulate matter.
- The optimal GO concentration that will lead to maximum performance of the engine with minimal emissions was determined to be 50 ppm. This blend showed performance characteristics that were nearly comparable to regular diesel for all the loads. The nano additives of graphite oxide, especially at a concentration of 50 ppm, improved the performance of biodiesel from Tamanu oil.

This can be considered as a higher efficiency with better combustion, thus lower emission, and thereby making TME20+GO50 a very promising alternative fuel for diesel engines. Further work may be considered to optimize the nano additive with respect to reducing NO_x emissions while preserving the observed improvements.

5. Future Scope

While the short-term benefits of the GO-doped biodiesel blend are seen as a reduction in emissions and increase in performance, the long-term effects are areas that need much more research. Preliminary reports indicate that this stable dispersion characteristics of GO is not prone to injector clogging due to colloidal suspension stabilizing in fuel. Additionally, the lower level of soot and particulate matter emissions can also extend after-treatment system life. Nonetheless, the oxidative behavior of GO would make it pertinent to examine thoroughly in terms of tribology as increased catalytic activity might induce excessive wear of engine parts. Future experiments shall include analyses based on dissembled engines post running for considerable mileage to inspect for wear trends at critical sites of injectors, piston rings and cylinder walls.

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Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

Has this article screened for similarity?

Yes