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EFFECT OF GRAPHITE MICROPARTICLES AS ADDITIVE IN AN INDIRECT DIESEL ENGINE FUELLED WITH PURE PALM OIL

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ABSTRACT

Research lately has shown the prospects of graphite as an additive for diesel engines due to its favourable characteristics. Moreover, using pure palm oil (PPaO) as the primary fuel in diesel engines is not recommended because of numerous disadvantages. To overcome such a problem, the effect of graphite oxide (GO) and graphite powder (GP) microparticle as an additive on PPaO was investigated by analysing the diesel engine combustion performance and emissions. GO was prepared using the Hummers method. The use of PPaO as a single fuel led to a significant increase in opacity by up to 127.0% compared to diesel fuel (DF). However, adding GO and GP as fuel additives can significantly reduce opacity by up to 63.9%, improve thermal efficiency by up to 20.4%, and increase specific fuel consumption by up to 40.1% compared to DF. These results indicate that GO and GP have promising potential as effective fuel additives for PPaO, leading to increased combustion efficiency, and reduced hazardous emissions in diesel engine applications.

Keywords: diesel engine performance, graphite oxide, graphite powder, pure palm oil.

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INTRODUCTION

Diesel fuel is versatile and has applications in many industries, including transportation, locomotives, construction, mining, maritime, agriculture, military and stationary power generation (Ooi *et al*., 2016; Yilmaz *et al*., 2022a; 2022b). Moreover, alternative fuels for diesel engines have been widely developed by researchers, the most popular of which is biodiesel with various raw materials, followed by natural gas, LPG, methane, propane, hydrogen and others (Atmanli and Yilmaz, 2021; Geng *et al*., 2017; Kegl *et al*., 2013; Ropandi *et al*., 2022). Some of these fuels can be used directly in diesel engines, and some require other methods, such as dual fuel, blending and emulsification (Atmanli, 2020; Hoang *et al*., 2022; Kegl *et al*., 2021). Palm oil is one of the most popular biofuel sources to replace conventional diesel fuel derived from the oil palm tree. Palm oil is generally useful as the feedstock for food and cosmetics (Harahap *et al*., 2020; Xin *et al*., 2022). Indonesia is the largest palm oil producer in the world, with a production of up to 46.9 million tonnes in 2022 and has an excellent potential to utilise palm oil as an alternative fuel in diesel engines (Farobie and Hartulistiyoso, 2021; Sani *et al*., 2018).

Palm oil biodiesel (POB) which is produced from crude palm oil (CPO), is a clean, renewable fuel characterised by higher flash points, lubricity, combustion efficiency, cetane number, biodegradability, and non-toxicity compared to conventional diesel fuel (Dey *et al*., 2021). However, the development of POB has several obstacles, particularly the production process, which could be more complicated (Pipitone and Costanza, 2018). Moreover, using CPO directly in a diesel engine is not recommended because it prompts several undesirable consequences, including increased fuel consumption, decreased engine power performance and forming carbon deposits in the combustion chamber (Syarif *et al*., 2017; Yilmaz *et al*., 2017). Besides, many studies have been conducted over the last two decades to evaluate the use of pure palm oils as diesel fuel. The high viscosity of PPaO limits fuel atomisation and enhances fuel spray penetration, leading to engine deposits and the thickening of lubricating oil (De Almeida *et al*., 2002).

Several works have been done to enhance engine performance and emissions, such as combustion treatments, engine configuration options, biofuel utilisation, and fuel additive (Atmanli, 2016; Sebayang *et al*., 2022; Zhao *et al*., 2023). Fuel additives are one of the most cost-effective methods for mitigating the rising diesel pollution emissions and increasing engine performance. Substantial research is currently being conducted into using nanoscale materials as fuel additives for diesel engines (Ooi *et al*., 2016). Multiwall carbon nanotube (MWCNT), carbon nanotube (CNT), aluminium oxide (Al_2O_3), silicon oxide (SiO_2), alumina, graphite oxide (GO), graphene and many other nanomaterials were utilised as additives in diesel fuel. MWCNT and alumina had been used as additives in jatropha biodiesel. It was found that adding MWCNT reduced the ignition delay and improved combustion performance (Sonara and Rathod, 2021).

A numerical investigation of MWCNT as a fuel additive in diesel fuel has been reported (Sa *et al*., 2021). The result showed that the addition of MWCNT and graphene nanoplatelets (GNP) could increase the coefficient of heat transfer rate and pressure drop. Vellaiyan (2019) performed research applying CNT additions in soybean biodiesel in diesel engines. It was found that soybean biodiesel and its mix promote a shorter ignition delay time, reduced in-cylinder pressure and net heat release rate compared to diesel fuel.

Chen *et al*. (2018) used CNT to compare the effects of using nanoparticles of Al_2O_3, CNT, and silicon oxide (SiO_2) as additives in diesel engines. It was found that CNT has better brake-specific fuel consumption (BSFC), high brake thermal efficiency (BTE) and low CO emission compared to Al_2O_3 and SiO_2. Razzaq *et al*. (2021) employed B30 palm biodiesel with GNP and dimethyl carbonate (DMC) as fuel additives. The results show improved BTE and BSFC at all engine speeds, significantly reducing HC emissions (Ooi *et al*., 2016; 2017) examine GO using as a fuel additive. In this investigation, GO was found to be highly efficient in enhancing the combustion properties of diesel fuel and lower pollutant emissions.

However, there is no published research to investigate PPaO as primary fuel with GP and GO microparticles as fuel additives in indirect diesel engines, most of them focus on additive nanoparticles and use biodiesel and diesel fuel as the primary fuel. Thus, this topic is becoming quite interesting to explore. Hence, the current study aims to investigate the performance and emission characteristics of the indirect diesel engine fuelled with PPaO with GO and GP microparticles as fuel additives. The fuel was prepared by blending PPaO with GO and GP using ultrasonic methods. The baseline fuels for comparing engine performance and emissions were diesel fuel and PPaO.

MATERIALS AND METHODS

Experimental Apparatus

The schematic layout of the engine bench is illustrated in *Figure 1*. The engine power

performance was calculated and analysed. The exhaust smoke was measured utilising a smoke meter. *Table 1* shows the test engine's specifications. To ensure the experiment's validity and the precision of the data, each component of equipment and item of equipment was checked and adjusted to its proper settings before performing the experiments. Each operational point was measured several times to reduce error. After more than 10 min of stable operation, the data were collected thrice under identical operating conditions.

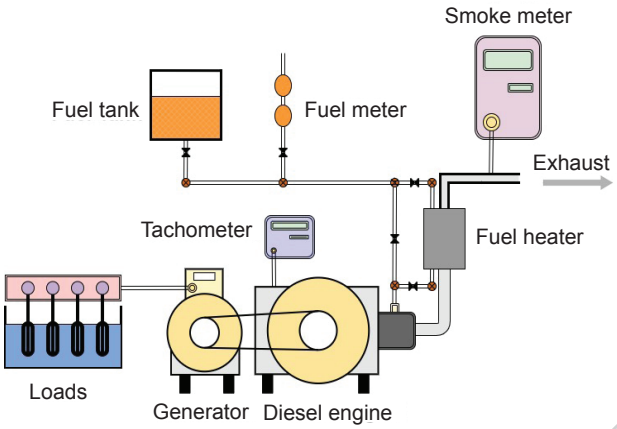

Figure 1. Schematic of engine test.

TABLE 1. SPECIFICATION OF THE TEST ENGINE

Specification	Dafeng S195
Type	Four stroke, Indirect injection, Single cylinder
Bore × Stroke	95 mm × 115 mm
Cylinder volume	0.815 L
Compression ration	22 : 1
Engine max power rate	14 hp / 2200 rpm
Generator rated power	7500W at 1500 rpm

Test Fuel

In this study, diesel fuel (DF) was utilised as the baseline fuel for comparison. PPaO was prepared as the primary fuel for the diesel engine. Preheating of PPaO was conducted in fuel lines at temperatures 60°C-100°C to lower the viscosity of PPaO and avoid clogging in the fuel line and injector. A similar approach was used by (De Almeida *et al*., 2002). The additive material utilised in this study was GP. The Hummer technique was used to synthesise GO, and the procedure was continued by mixing PPaO with GP and GO. The sonication method is utilised in this process to provide a medium for the mixing of fuel, as seen in *Figure 2*, the formulation of test fuel can be seen in *Table 2*. The test fuel properties of DF, PPaO and PPaO blended of additives of GP and GO are presented in *Table 3*.

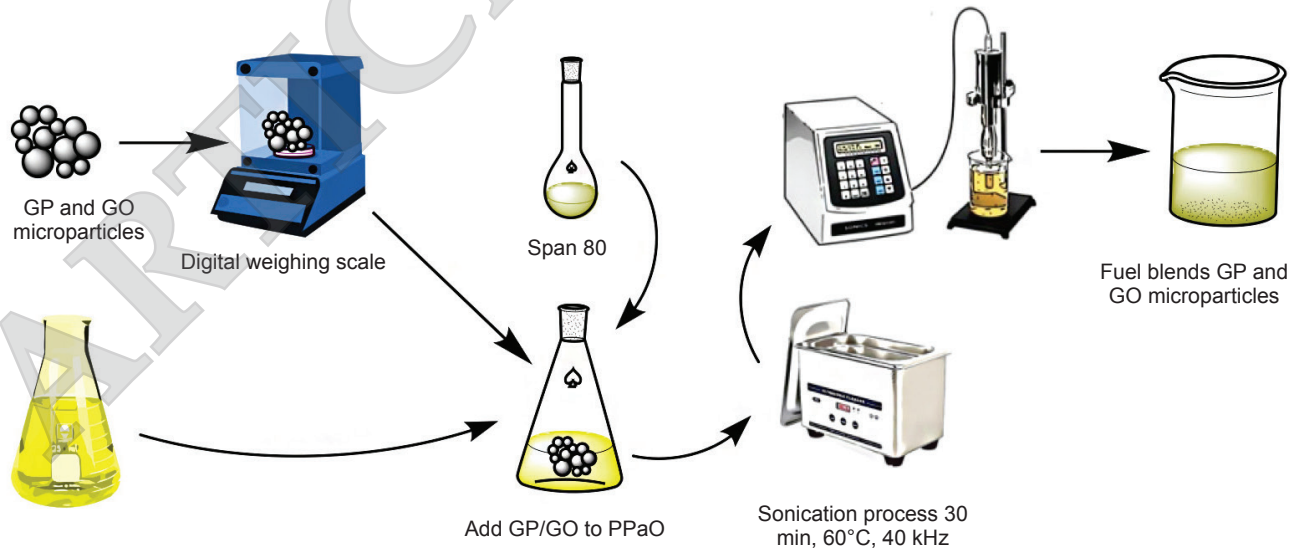

Figure 2. The mixing process of PPaO with additives of graphite powder and graphite oxide.

TABLE 2. THE PREPARATION OF THE FUEL SAMPLE

Formulation	Dosage of additive	Dosage of surfactant	Label
Diesel fuel	-	-	DF
Pure palm oil	-	-	PPaO
PPaO + Graphite powder	Graphite powder (150 ppm)	-	PPaOG
PPaOG + Span 80	Graphite powder (150 ppm)	Span 80 (20 mL)	PPaOGS
PPaO + Graphite oxide powder	Graphite oxide (150 ppm)	-	PPaOGO
PPaOGO+ Span 80	Graphite oxide (50 ppm)	Span 80 (20 mL)	PPaOGOS

Note: PPaOG - Pure palm oil graphite powder; PPaOGO - Pure palm oil graphite oxide.

TABLE 3. TEST FUEL PROPERTIES

Formulation label	Lower heating value (kcal/kg)	Viscosity (cP)	Density (kg/m^3)	Flash point (°C)
DF	10 536	2.852	844.4	28
PPaO	9 735	49.740	908.8	56
PPaOG	9 420	46.832	912.4	38
PPaOGS	9 432	48.841	909.2	50
PPaOGO	9 462	46.114	906.9	42
PPaOGOS	9 485	49.273	908.9	40

Note: PPaOGS - Pure palm oil graphite powder surfactant; PPaOGO - Pure palm oil graphite oxide; PPaOGOS - Pure palm oil graphite oxide surfactant.

Material Characterisation

The particle size distribution was measured using particle size analysis based on light scattering (Horiba SZ-100). The Fourier transform infrared spectroscopy (FTIR) of the sample was obtained. Scanning electron microscope (SEM) was used to study the morphologies of GP and GO and energy dispersive X-ray spectroscopy (EDS) analysis was utilised to determine the elemental composition of GP and GO as well as their distribution. Both of SEM and EDS were performed on HITACHI SU3500. The crystal structure of materials was analysed using X-ray diffractometer (XRD) Bruker D8 Advance diffractometer with Cu Kα radiation (λ =1:54060Å).

Engine Performance Analysis

Several characteristics, such as engine power, torque, specific fuel consumption and thermal efficiency, are required to determine engine power performance.

Engine power (Pe).

$$Pe = \frac{V.I.\cos\phi}{1000.\eta_{generator}} (kW) \quad (1)$$

where V is voltage (V), I is Ampere (I), is power factor for one single phase is 1 and is electric generator efficiency for engines under 50 kVA is 87%-89%; for generators employing V belts, the power generated is divided by 0.96 (Belt efficiency) (Khairil *et al*., 2020).

Engine torque (Te).

$$Te = \frac{6000.\ Pe}{2.Phi.\ N} (kW) \quad (2)$$

where Pe is the engine power, Phi is 3.14 and N is the engine rotation (RPM).

The specific fuel consumption (SFC). The specific fuel consumption (SFC) is described as the quantity of fuel the engine uses to generate power, expressed in kW/h. The SFC may be computed using the following equation (Khairil *et al*., 2020).

$$SFC = \frac{\dot{m}fuel}{Pe} \quad (3)$$

where SFC is the specific fuel consumption (kg/kWh), is fuel mass flow (kg/hr) and Pe is the engine power (kW).

Thermal efficiency. The heat-use efficiency of fuel to be transformed into mechanical work is characterised as thermal efficiency. The equation may be used to compute the thermal efficiency (Khairil *et al*., 2020).

$$\eta th = \frac{Pe \,.632{,}5}{\dot{m}\, fuel \,.\ \mathrm{LHV}} \qquad (4)$$

where ηth is the thermal efficiency (%) and LHV is the lower heating value (kcal/kg).

RESULTS AND DISCUSSION

Microparticles of GP and GO

Particle size analysis (PSA). It is a critical technique in materials science and engineering for understanding the physical properties of materials. PSA provides information about the size distribution of particles in a sample, which is essential for understanding the behaviour of the material. PSA is used to analyse various materials, including powders, suspensions, emulsions, and aerosols. PSA techniques include light scattering, sedimentation, and microscopy-based methods. Each technique has its advantages and disadvantages, and the choice of technique depends on the properties of the material being analysed. Particle size analysis based on light scattering is a method of determining the velocity of Brownian motion by analysing the fluctuations of scattered light by particles in suspension when illuminated with a laser. This velocity can then be used to calculate the hydrodynamic size of particles using the Stokes-Einstein relationship (Hussain *et al.*, 2020). According to the measurements illustrated in *Figure 3(a)*, the average particle size of graphite powder is 1.8 µm, mean 2.3 µm, standard deviation 2.8 µm with medium dispersion viscosity of 0.896 mPa.s.

Fourier transform infrared (FTIR) spectroscopy. It is a powerful analytical technique used to identify and characterise materials. FTIR is a method for identifying and quantifying some material constituents, including fuel and the chemical composition of the environment. FTIR is one of the analytical methods that is frequently applied due to the factors such as cost, speed, and screening quality. This procedure uses a molecular "fingerprinting" technique (Riayatsyah *et al.*, 2021). *Figure 3(b)* shows the results of the FTIR synthesised from graphite powder to graphite Oxide as an additive. As seen in *Table 4*, the FTIR results of the additive effect, such as wavenumber, group attribution, absorption intensity, and vibration type of the absorption peaks, have been detected. The graphite spectrum tends not to have a typical absorption from the oxide functional group unless there is absorption in the wave number region of 1800-2200 cm^{-1}, a characteristic of chemical precursors (refined oil) with molecular vibrations of C=O stretching. As for the graphite oxide spectrum, a new broad spectrum is formed at a wave number of 3653 cm^{-1}, a stretching vibration, and at 1000-1300 cm^{-1}, a bending vibration for the O-H functional group.

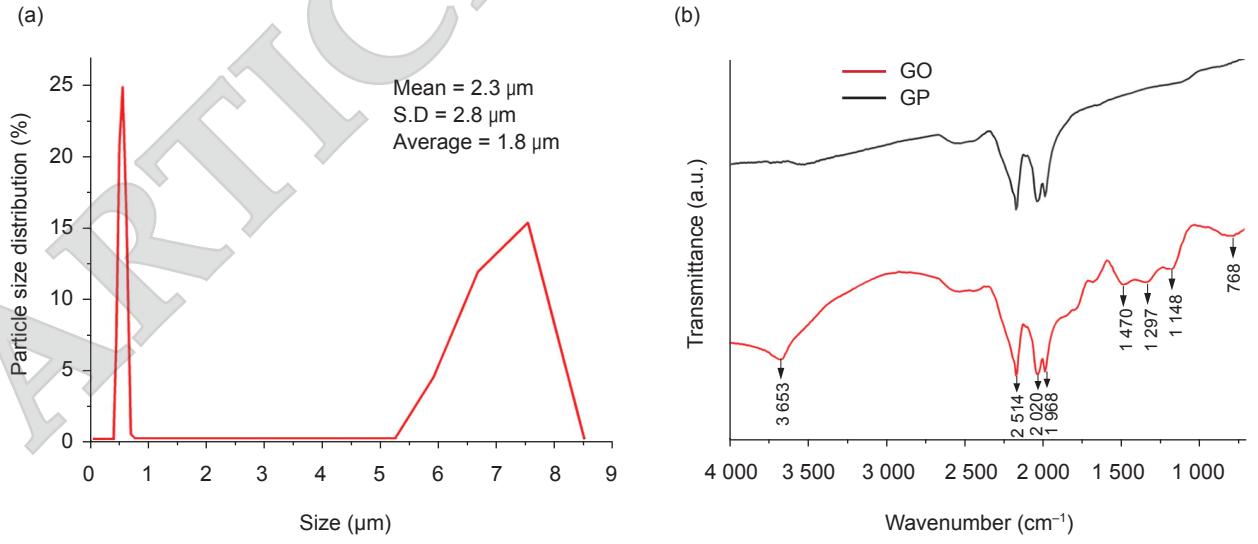

Figure 3. (a) Particle size analysis based on light scattering of graphite powder (b) the FTIR Spectra synthesised from graphite powder to graphite oxide.

TABLE 4. THE FTIR OF THE ADDITIVE

Wavenumber (cm^1)	Group attribution	Vibration type	Absorption intensity
3 653	O–H	Stretching	Broad, Strong
2 154	C=O carbonyl	Stretching	Sharp, Strong
2 020	C=O	Stretching	Sharp, Strong
1 968	O–H	Bending	Sharp, Strong
1 470	C–H	Bending	Broad, Strong
1 297	C–OH	Stretching	Broad, Weak
1 148	C–O–C	Stretching	Broad, Weak
768	CH2	Stretching	Broad, Weak

Scanning electron microscope (SEM). It is a powerful tool that has revolutionised the field of materials science by enabling high-resolution imaging of surface morphology and microstructure. SEM in this study was used to investigate the morphology and microstructure of GP and GO, as seen in *Figures 4a* and *4b* it was found that GP exhibited a layered structure, with thin and flat graphite flakes stacked on top of each other. The SEM images revealed that the flakes had irregular edges and a size range of 5-10 μm. The microstructure analysis showed that the graphite flakes had a crystalline structure with well-defined basal planes and high aspect ratios. *Figures 4c* and *4d* showed that GO exhibited a flake-like morphology, with a size range of 0.1-5.0 μm. The SEM images revealed that the surface of the GO flakes was rough and porous, with many wrinkles and folds. The microstructure analysis showed that the GO flakes had a layered structure with an interlayer spacing of 0.8 nm, consistent with the presence of oxygen-containing functional groups. The average thickness of the GO flakes was found to be approximately 10 nm. The layered structure of GO is due to the oxidation of the graphite layers, which results in the formation of oxygen functional groups on the surface. The crumpled and wrinkled morphology of GO is believed to be caused by the interactions between the oxygen functional groups and the surrounding environment. The irregular edges of the GO flakes are consistent with the presence of oxygen functional groups, which can cause structural defects and irregularities.

Energy-dispersive X-ray spectroscopy (EDS). EDS is a widely used analytical technique for elemental analysis of materials. EDS is a non-destructive technique that can be performed on a wide range of materials, including metals, ceramics, polymers and biological samples. The technique involves the detection and measurement of X-rays emitted from a sample when it is bombarded with an electron beam. The energy and intensity of the X-rays are used to identify and quantify the elements present in the sample. EDS has several advantages over other analytical techniques, including high sensitivity, rapid analysis and non-destructive analysis (Hernandez C *et al.*, 2022). The EDS analysis of GO, as seen in *Figure 5a* was found to contain carbon, oxygen, and traces of other elements. The atomic percent composition of carbon and oxygen in GO was found to be 55.63% and 39.43%, respectively. These results are consistent with the expected composition of GO based on its chemical structure and properties. The EDS analysis of GO confirmed the presence of carbon and oxygen, which are the main elements in GO. The atomic percent composition of carbon and oxygen in GO was consistent with previous studies that used different techniques to analyse the elemental composition of GO. The traces of other elements detected in the EDS analysis may be due to impurities in the GO sample or contamination during the sample preparation.

X-ray diffraction (XRD). XRD analysis is a widely used technique for determining the crystal structure of materials. XRD analysis was conducted on GP to investigate its crystal structure and identify its characteristic peaks. The GP sample was prepared as powder. XRD analysis was performed using a Bruker D8 Advance X-ray diffractometer with Cu Kα radiation (λ=1.5406 Å) in the 2θ range of 10° to 80° with a step size of 0.02° and a scanning rate of 0.5°/min. The XRD pattern of graphite powder is shown in *Figure 5b*. The diffraction peaks at 2θ angles are 26.55°, 44.30°, 54.60° and 77.50° which correspond to the (002), (100), (004) and (110) planes of the hexagonal crystal structure of graphite, respectively. The results show that the graphite powder has a typical hexagonal crystal structure with characteristic diffraction peaks at 2θ angles of 26.50°, 44.30°, 54.70° and 77.50° are matching with The International Centre for Diffraction Data (ICDD) Graphite 00-008-0415. The obtained XRD pattern was compared with research done by Ahmad Daud *et al.* (2017), and the results confirmed the identification of the sample as graphite.

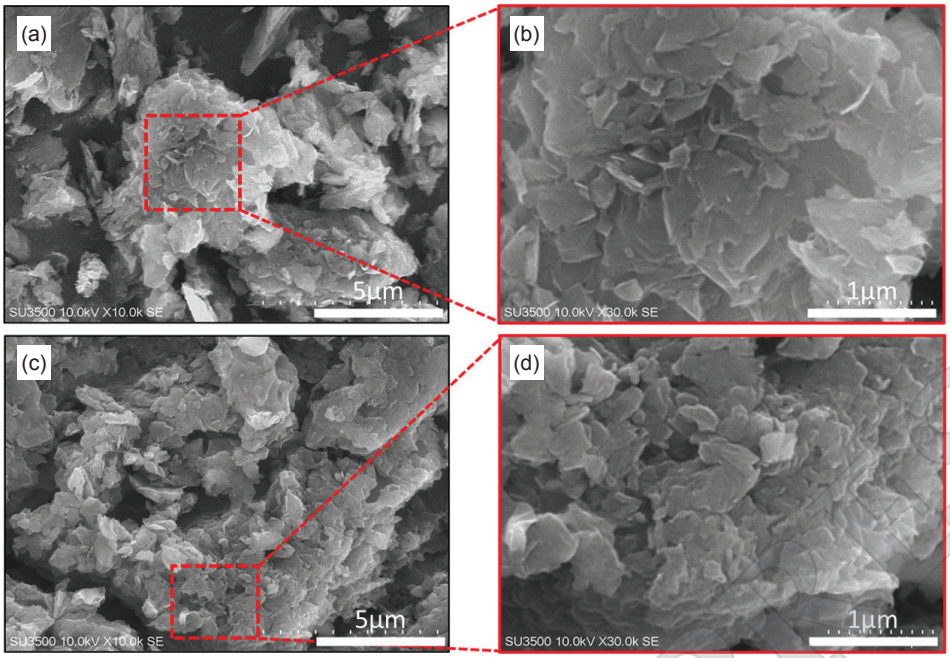

Figure 4. SEM images of (a -b) graphite powder and (c-d) graphite oxide.

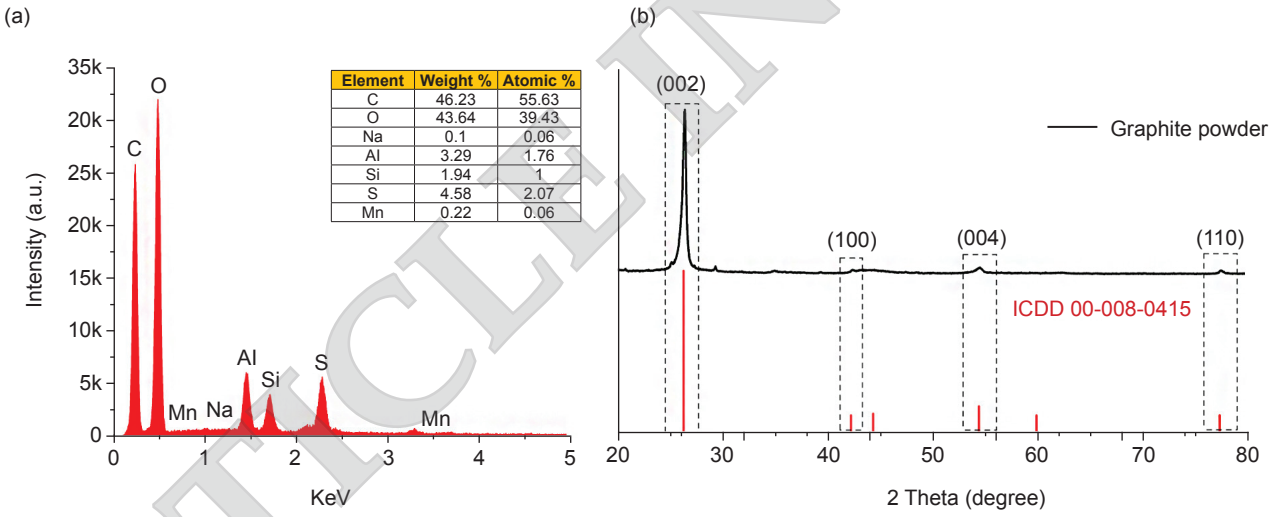

Figure 5. (a) EDS spectra and element analysis of graphite oxide, and (b) XRD spectra of graphite powder.

Power Performance

Engine power and torque are important parameters that determine the performance of an engine. Power is the rate at which work is done, while torque is the twisting force produced by the engine. Based on the experiment, the engine power and torque were estimated. A comparison chart with an error bar of the engine power and torque is illustrated in *Figure 6*. The result showed that the engine fuelled with pure palm oil graphite powder (PPaOG) produced lower power and torque than other fuels. The maximum engine power and torque decreased using PPaOG was 18% at 100% load, with the highest average power loss was 29.5% compared to DF. The increase in engine power and torque may be ascribed to the energy created in the cylinder because of an increase in the surface-to-volume ratio of the additive, as well as an increase in the heat transfer coefficient owing to the additives in the fuels (Heidari-Maleni *et al.*, 2020). The low heating value is one of the

factors that contributes to the decreased engine power and torque that occurs when PPaO is used. *Figure 6* illustrates an important finding that the use of pure palm oil graphite oxide surfactant (PPaOGOS) leads to engine power and torque that are comparable to those produced by DF. This indicates that PPaOGOS has the potential to achieve similar performance levels as DF in terms of engine power and torque. Utilising PPaOGOS as the main fuel may increase the combustion rate due to the quick burning of PPaOGOS during the premixed combustion stage. Other causes for the increase in engine power and torque are oxygen content in PPaOGOS, and a similar result was conducted by (Hoseini *et al.*, 2020).

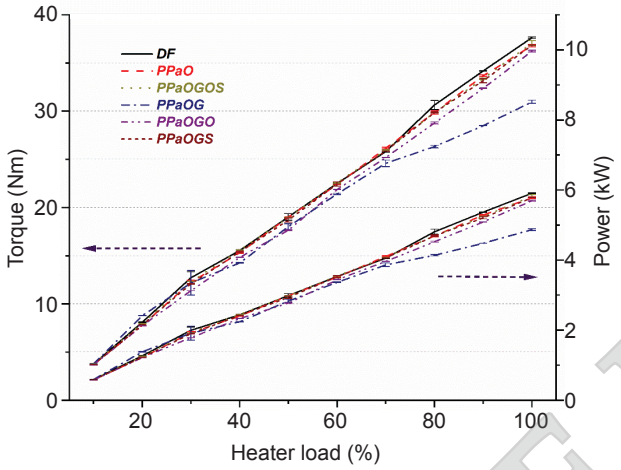

Figure 6. Comparison of power and torque with engine load.

Fuel Economy

Specific fuel consumption (SFC) and thermal efficiency are important performance parameters of an engine, which significantly impact its operation. SFC represents the amount of fuel consumed per unit of power output, while thermal efficiency is the ratio of the useful work output to the heat input. The engine load has a noticeable effect on both SFC and thermal efficiency, as shown in *Figure 7*. The findings demonstrate that at a load of 73.0%, PPaOG exhibits the highest increase in SFC, with a rise of 40.1%, and an average SFC of about 12.6% compared to DF. This is attributed to the fact that DF has a lower density and higher calorific value than PPaOG and other fuels, causing PPaOG to consume more fuel to produce the same amount of power as DF. Similar results were observed for other fuels blended with PPaO. These findings align with prior research conducted by (Radhakrishnan *et al.*, 2018; Syarif *et al.*, 2017).

In addition, the thermal efficiency of PPaO and PPaO blended with GP and GO was discovered to be higher than that of DF. The most significant increase in thermal efficiency was observed in PPaOG at an 82.0% load, with a rise of 20.4%. This is because PPaO has a lower calorific value than DF, resulting in a smaller energy input to the system while still delivering comparable engine power. Moreover, using GO as an additive enhances thermal efficiency more than GP, since the oxygen in PPaO combined with GO results in better fuel and air mixing, leading to increase efficiency. These findings are consistent with those of Syarif *et al.* (2017), who also reported a similar increase in thermal efficiency.

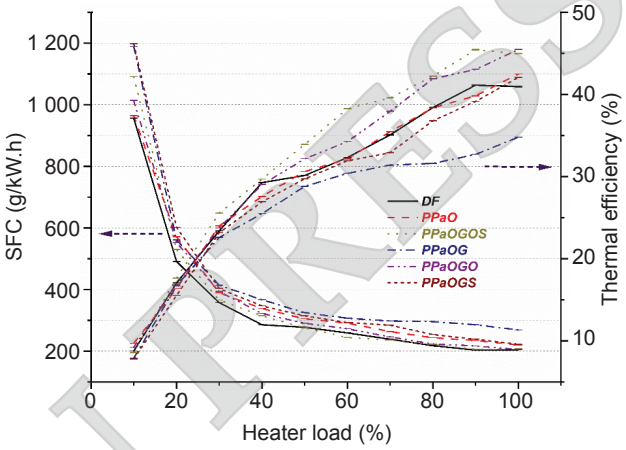

Figure 7. Comparison of SFC and thermal efficiency with engine load.

Smoke Emission

Diesel engines are known to emit significant amounts of particulate matter, which can have adverse effects on human health and the environment. Smoke opacity is a crucial indicator of the level of particulate matter emissions from diesel engines. Factors such as inadequate oxygen levels, longer oxidation residence time, and high in-cylinder temperatures all contribute to higher exhaust emissions, negatively impacting human health and the environment (Lv *et al.*, 2022). As illustrated in *Figure 8*, the use of PPaO resulted in a 127% increase in opacity, which is significantly higher compared to DF fuel. This can be attributed to the fact that PPaO has a much higher viscosity, ten times higher than DF, which leads to the formation of larger droplets that are difficult to burn and could result in incomplete combustion when entering the combustion chamber. On the other hand, the addition of GP and GO to PPaO significantly reduced the opacity, with the highest decrease observed for PPaOGOS by 63.9% compared to DF. Previous studies (Gavhane *et al.*, 2021; Prabu, 2018; Shaafi and Velraj, 2015) reported that adding nanomaterial additives to diesel and biodiesel can effectively reduce CO emissions. The addition of graphite and graphite oxide additives can serve as a fuel catalyst, which helps to smoothen the fuel droplets and leads to micro-explosions, making them more flammable and producing a better combustion process.

Interestingly, Appavu and Venkata Ramanan (2020) found that the emissions of fuel containing nanoparticles are significantly lower than those of diesel at full load, as the nanoparticles can boost the atomisation rate and redox properties of the fuel, leading to complete combustion. In summary, the addition of GP and GO to PPaO has proven to be an effective method for reducing diesel engine opacity and improving combustion efficiency. Moreover, the use of alternative fuels, including those with nanomaterial additives, could potentially contribute to long-term reductions in urban pollution and fossil fuel consumption.

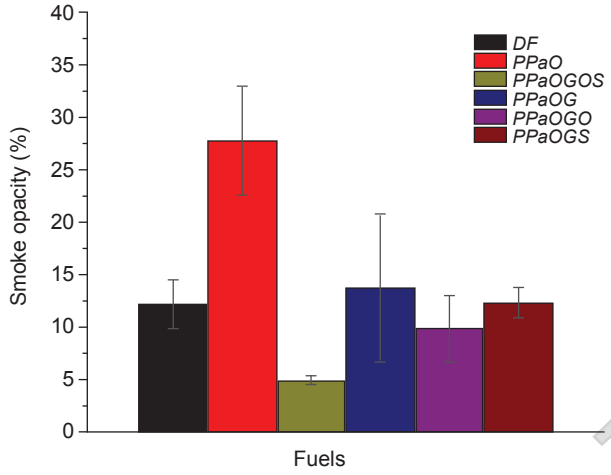

Figure 8. Smoke opacity emission.

CONCLUSION

The effects of adding fuel additives of GO and GP to diesel fuel and PPaO were investigated. It was found that the addition of GO and GP in PPaO improved the fuel properties such as LHV, flash point, viscosity. The SEM images revealed that the GO and GP particles were uniformly distributed in the fuel matrix, facilitating the heat transfer, and promoting the formation of a stable flame front.

In this study, the viscosity of diesel fuel was reduced through preheating, and the effects of adding GP and GO to PPaO were investigated. The results showed that the addition of GP and GO to PPaO significantly increased opacity by 127.0% compared to DF. Interestingly, the use of PPaOGOS resulted in a lower opacity, with a reduction of 63.9% compared to PPaO. The observed differences in opacity could be attributed to the varying sizes and shapes of the graphite particles, which affect light scattering in the fuel.

The study also evaluated the thermal efficiency of the fuels, with the highest thermal efficiency observed for PPaOG at a load of 82.0%, with an increase of 20.4% compared to DF, and an average increase of 0.3% with the use of the additive. However, it is worth noting that an increase in SFC was observed, with PPaOG showing the maximum increase at a load of 73.0%, with a rise of 40.1% compared to DF, and an average increase of about 12.6%. This increase in SFC may be due to the additional energy required to break down the larger graphite particles, which reduces the overall fuel energy efficiency.

Overall, the addition of graphite powder and graphite oxide to PPaO was found to be an effective approach to reduce diesel engine opacity and increase thermal efficiency compared to DF. These findings suggest that alternative fuels for diesel engines, such as PPaO with graphite powder and graphite oxide additives, could potentially contribute to the long-term reduction of urban pollution and fossil fuel consumption. Further research is needed to fully evaluate the potential benefits and drawbacks of alternative fuels and additives for diesel engines.

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