

Effects of Load on the Emission and Performance Properties of a Compression Ignition Engine Run on Modified Biodiesel

Benedict Christopher^{1*}, Kamen F. L², Ndukwe O. C², Walter Peter Echeng¹, Ofoluwanyo Omamuyovwi Rosemary¹

¹Department of Chemical Engineering, Federal Polytechnic Nekede, Owerri

²Department of Chemical Engineering, Federal University of Technology, Owerri

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*Corresponding author: Benedict Christopher

Department of Chemical Engineering, Federal Polytechnic Nekede, Owerri

Abstract

This study investigated the effect of engine load on the performance and emission characteristics of a compression ignition engine fuelled with watermelon seed oil methyl ester (WOME) modified with metal and oxygenated additives. Watermelon seed oil was extracted and converted to biodiesel through acid esterification followed by alkaline transesterification. The oil yield was 48.7828%, while the biodiesel yield was 85.28 vol.%. Acid esterification reduced the free fatty acid content from 5.4464 to 2.347 mg/g, facilitating effective alkaline transesterification. The physicochemical properties of the produced WOME included a density of 0.881 g/cm³, kinematic viscosity of 3.146 mm²/s, moisture content of 0.0389%, cetane number of 57.34, flash point of 94°C, and cloud point of -6°C, indicating favourable fuel characteristics for compression ignition engine applications. The WOME was blended with petroleum diesel and modified with copper (II) oxide (CuO), copper (II) sulphate (CuSO₄), and acetoacetic ester (Ace), and the resulting fuel blends were tested under varying engine loads. The results showed that engine load significantly influenced fuel consumption, brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), exhaust gas temperature (EGT), and gaseous emissions. At a 30 kg load, the lowest BSFC recorded was 0.2438 kg/kW-hr, while the highest BTE was 38.06%. Increasing engine load generally increased fuel consumption, H₂S, NO₂, CO, and EGT, while CH₄ emissions decreased. The optimized WOME blend demonstrated the best overall engine performance and the lowest overall emissions, with the minimum CH₄ emission of 52.7 ppm. The study concludes that watermelon seed oil is a promising renewable feedstock for biodiesel production and that modification of WOME with CuO, CuSO₄, and acetoacetic ester can improve engine performance and emission characteristics under varying load conditions. The findings demonstrate the potential of additive-modified WOME-diesel blends as a cleaner and more efficient alternative to conventional petroleum diesel in compression ignition engines.

Keywords: Watermelon Seed Biodiesel, Compression Ignition Engine, Engine Load, Additives, Engine Performance, Exhaust Emissions.

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1.0 INTRODUCTION

Countries around the world are increasingly recognizing the need to reduce dependence on fossil fuels because their extensive utilization contributes substantially to global warming through the continuous release of greenhouse gases (GHGs) into the atmosphere. This phenomenon has intensified concerns about climate change and its associated environmental consequences. In addition, fossil fuel resources are finite and are progressively being depleted. The increasing demand for transportation fuels, coupled with concerns over energy security and fluctuations in petroleum prices in the global market, has further emphasized the need to develop

sustainable and reliable alternatives to conventional fossil fuels (Mulk *et al.*, 2026; Zheng & Cho, 2024).

Global warming is one of the most significant environmental challenges facing the world today. It is primarily driven by the increasing concentration of greenhouse gases (GHGs) in the atmosphere arising from human activities, particularly the prolonged dependence on fossil fuels since the onset of industrialization (IPCC, 2023). The combustion of conventional petroleum-based fuels releases various harmful exhaust pollutants, including nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons (HC), carbon dioxide (CO₂), and

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particulate matter (PM). The adverse environmental consequences associated with fossil-fuel utilization have consequently stimulated extensive research into cleaner and renewable energy alternatives. Biofuels have emerged as promising substitutes because of their potential to reduce reliance on petroleum-derived fuels and support the decarbonization of the transportation sector. However, the extent of their greenhouse-gas reduction benefits depends on factors such as feedstock type, production processes, land-use implications, and overall lifecycle emissions (IEA, 2024).

Biodiesel derived from renewable biological resources has emerged as a promising substitute for conventional diesel fuel. Several non-edible vegetable oils have been investigated as potential feedstocks for biodiesel production, including castor oil (Ahmed *et al.*, 2024; Mulk *et al.*, 2026), *Jatropha curcas*, *Pongamia pinnata* (karanja), neem seed, rubber seed, mahua, and tobacco seed oils (Shaah *et al.*, 2021; Jamil *et al.*, 2023). Biodiesel is primarily composed of long-chain mono-alkyl esters and is commonly produced through the transesterification of vegetable oils or animal fats. Its renewable origin, biodegradability, and potential to reduce certain exhaust pollutants have made it an important alternative fuel for compression ignition (CI) engines. However, biodiesel produced from edible oils is often associated with relatively high production costs and raises concerns regarding competition with food resources. Consequently, research has increasingly shifted towards non-edible oils as more sustainable and economically viable biodiesel feedstocks (Zheng & Cho, 2024).

Although biodiesel possesses several environmental and renewable-energy advantages, its application in CI engines is associated with some limitations. Compared with conventional petroleum diesel, biodiesel generally exhibits higher viscosity and pour point and lower volatility. The relatively high viscosity can adversely affect fuel atomization, spray characteristics, evaporation, and mixing with air, thereby influencing combustion and engine performance (Zheng & Cho, 2024; Le *et al.*, 2024). Nevertheless, biodiesel contains little or no sulfur and aromatic compounds and can be utilized in diesel engines while potentially reducing some environmentally harmful emissions compared with conventional petroleum-derived fuels (Le *et al.*, 2024).

Previous research has demonstrated the potential of fuel additives to overcome some of the limitations associated with biodiesel use. Ndukwe and Adeyemo (2021) investigated WOME20D80 blended with additives in a compression ignition engine operated at 2000 rev/min and a 10 N load. Their findings identified WOME Y as the most effective blend for emission characteristics, while WOME X produced the best engine performance. The study reported reductions of approximately 45% in H₂S emissions, 26% in CO

emissions, 20% in exhaust gas temperature (EGT), and 37.5% in fuel consumption (FC).

More recent investigations have shown that the incorporation of nano-additives into biodiesel blends can substantially improve combustion and engine characteristics. Metal oxide nanoparticles, including Al₂O₃, CeO₂, CuO, TiO₂, Fe₂O₃, and MnO, can enhance fuel atomization and oxygen availability during combustion, thereby improving brake thermal efficiency (BTE), reducing brake-specific fuel consumption (BSFC), and lowering emissions of CO, HC, smoke opacity, and particulate matter. The use of hybrid nano-additives has also been associated with improved combustion stability and enhanced engine performance under different operating conditions (Gad *et al.*, 2024; Ahmed *et al.*, 2024; Zheng & Cho, 2024).

Several researchers, including El-Seesy *et al.*, (2021), Soudagar *et al.*, (2022), Ranjith *et al.*, (2022), Elkelawy *et al.*, (2022), and Kumar *et al.*, (2023), have reported improvements in engine performance and reductions in exhaust emissions following the incorporation of nano-metallic additives into biodiesel and diesel fuels. Materials such as Al₂O₃, carbon nanotubes (CNT), CuO, ZnO, CeO₂, and iron-based nanoparticles have been reported to promote improved combustion, with appropriate concentrations resulting in reduced BSFC and increased BTE. However, the effectiveness of these additives is strongly dependent on their concentration. Increasing nanoparticle concentration does not necessarily produce continuous improvements in engine performance or emissions. In several studies, intermediate concentrations produced better results than higher concentrations, indicating the existence of an optimum additive dosage for achieving desirable combustion characteristics.

Engine operating conditions, particularly load, also have a significant influence on fuel consumption, performance, combustion behavior, and exhaust emissions. In general, brake thermal efficiency tends to increase as engine load increases because a greater proportion of the available fuel energy is effectively converted into useful brake power. Conversely, increasing engine load generally results in higher fuel consumption and exhaust gas temperature and may promote increased NO_x formation because of the higher combustion temperatures. The addition of nano-additives to biodiesel blends has been reported to moderate some of these adverse effects by enhancing fuel-air mixing, improving combustion completeness, and promoting more efficient utilization of the fuel. Consequently, the combined influence of biodiesel composition, additive type and concentration, and engine load is an important consideration in developing optimized alternative fuels for compression ignition engines (Gad *et al.*, 2024; Mulk *et al.*, 2026; Fuel Additives for Biodiesel Systematic Review, 2026).

2. MATERIALS AND METHODS

2.1 Materials

Watermelon seeds were used as the primary feedstock. The major chemicals and reagents included methanol, potassium hydroxide (KOH), concentrated sulphuric acid (H_2SO_4), copper oxide (CuO), copper (II) sulphate (CuSO_4), acetoacetic ester, n-hexane, petroleum ether, ethanol, chloroform, potassium iodide, sodium thiosulphate, phenolphthalein, starch indicator, alcoholic KOH, distilled water and anhydrous sodium sulphate.

2.2 Preparation of Watermelon Seeds

Watermelon fruits were obtained from Relief Market, Owerri, Imo State, Nigeria. The seeds were manually removed from the fruits, washed to remove adhering dirt and impurities, and sun-dried for seven days. The dried seeds were subsequently milled to increase their surface area and improve solvent extraction. The milled material was sieved to obtain a relatively uniform particle size of about 0.5–1.0 mm.

2.3 Extraction of Watermelon Seed Oil

Oil was extracted from the prepared watermelon seed material using n-hexane as the extraction solvent in a Soxhlet apparatus. Extraction was conducted in batches because of the limited capacity of the extractor. After extraction, the recovered oil was heated for approximately 20 min to remove residual solvent. The oil yield was calculated from the mass of oil recovered relative to the mass of seed material used.

2.4 Degumming and Drying of Oil

The extracted oil was degummed using warm distilled water at approximately 73°C. The mixture was stirred and allowed to stand before centrifugation at 1600 rpm for 20 min. The upper phase was decanted and the treated oil was subsequently dried at 105°C for 2 h 30 min to reduce residual moisture.

2.5 Acid Esterification

The free fatty acid content of the degummed oil was first determined by titration. Because the initial FFA level was relatively high, acid esterification was employed before alkaline transesterification. The oil was heated to 60°C for 10 min. Methanol equivalent to 45% of the oil volume and concentrated sulphuric acid equivalent to 1.2% of the oil volume were added. The mixture was stirred at approximately 60°C and 321 rpm for 2 h. Following reaction, the mixture was transferred to a separating funnel and allowed to settle for 24 h. The treated oil phase was separated and dried before determination of the FFA level. The FFA content was reduced from 5.4464 to approximately 2.347 mg/g after esterification, indicating that the pretreatment reduced the acidity sufficiently for subsequent alkaline transesterification.

2.6 Production of Watermelon Seed Oil Methyl Ester

Biodiesel was produced through alkaline transesterification. The procedure was based on the selected production conditions, involving a reaction temperature of 60°C and methanol equivalent to 20% of the oil volume. For a typical batch, 100 mL of esterified watermelon seed oil was heated to 60°C. A potassium methoxide solution was prepared by dissolving 0.52 g KOH in 20 mL methanol. The solution was mixed until the KOH dissolved and was subsequently introduced into the warmed oil. The reaction mixture was maintained at approximately 60°C with continuous agitation for about 1 h. After reaction, the product was transferred into a separating funnel and allowed to settle for 24 h. The lower glycerol and soap-rich phase was removed. The crude biodiesel was washed repeatedly with warm distilled water until the wash water became clear. The biodiesel was then dried at approximately 105°C. Biodiesel yield was calculated from the volume of biodiesel recovered relative to the volume of oil initially used.

2.7 Characterization of WOME

The produced watermelon seed oil methyl ester was characterized for density, kinematic viscosity, FFA, acid value, saponification value, iodine value, moisture content, cetane number, flash point and cloud point. Density was determined from measured fuel mass and volume. Dynamic viscosity was determined using a digital viscometer and converted to kinematic viscosity using the measured density. FFA and acid value were determined by titration using KOH and phenolphthalein. Iodine value was determined using Wijs' solution, potassium iodide and sodium thiosulphate. Saponification value was determined using alcoholic KOH followed by titration with hydrochloric acid. The cetane number and calorific value were estimated using the applicable empirical relationships based on the measured fuel properties. Flash point was determined using an automatic Pensky-Martens closed-cup flash-point tester, while cloud point was determined by controlled cooling and visual observation of the first appearance of cloudiness.

2.8 Preparation of Test Fuels

WOME was blended with petroleum diesel at 20:80 by volume to produce WOME20D80, which served as the biodiesel control blend. Two optimized additive formulations previously established by Ndukwe and Adeyemo (2021) were selected for the present investigation:

- i. 11 vol. % WOME + 80 vol. % D + 9 vol. % Ace
+ 50 $\frac{\text{mg}}{\text{kg}}$ CuO + 50 $\frac{\text{mg}}{\text{kg}}$ CuSO_4
(WOME11D80Ace9CuO50CuSO₄50) —
selected for optimum engine performance.
- ii. 11 vol. % WOME + 80 vol. % D + 9 vol. % Ace
+ 30 $\frac{\text{mg}}{\text{kg}}$ CuO + 50 $\frac{\text{mg}}{\text{kg}}$ CuSO_4
(WOME11D80Ace9CuO30CuSO₄50) —
selected for optimum emission characteristics.

The additives consisted of acetoacetic ester as the oxygenated compound and CuO and CuSO₄ as metal-based additives.

2.9 Engine Testing

Engine tests were conducted using a compression ignition diesel engine operated at a constant speed of 1500 rev/min. Petroleum diesel, WOME20D80, WOME11D80Ace9CuO50CuSO₄50 and WOME11D80Ace9CuO30CuSO₄50 were separately evaluated. Static loads of 5, 10, 15, 20, 25 and 30 kg were applied using an eddy-current dynamometer. The engine was allowed to stabilize at each operating condition before measurements were recorded. Fuel consumption was determined from the volume of fuel consumed from a calibrated burette over a measured period. Engine speed was monitored using a tachometer. Brake power was obtained from the dynamometer measurements, while BSFC and BTE were calculated from the measured fuel consumption, brake power and fuel heating value. The exhaust gas temperature was measured using an exhaust gas thermometer positioned in the exhaust stream. The gaseous emissions investigated were hydrogen sulphide (H₂S), nitrogen dioxide (NO₂), carbon monoxide (CO) and methane (CH₄). Individual gas detectors were inserted into the exhaust stream to measure the concentration of each pollutant.

3. RESULTS AND DISCUSSION

3.1 Fuel Properties of Watermelon Seed Oil Methyl Ester (WOME)

The fuel properties of watermelon seed oil methyl ester (WOME) were determined. The oil yield of 48.7828% demonstrates the potential of watermelon seed oil as a non-edible biodiesel feedstock, particularly because of its appreciable lipid content and favourable fatty acid composition (Adewuyi *et al.*, 2021; El Marji *et al.*, 2026). The degummed oil had an FFA content of 5.4464 mg/g, which necessitated acid esterification to reduce the FFA to 2.347 mg/g before alkaline transesterification. This pretreatment helps minimize soap formation and improve biodiesel conversion and separation (Mofijur *et al.*, 2021; Amador-Gómez *et al.*, 2025). A biodiesel yield of 85.28 vol.% was subsequently obtained. The produced WOME had a density of 0.881 g/cm³ and a kinematic viscosity of 3.146 mm²/s, both within acceptable ranges for biodiesel fuel. The density is slightly higher than that of petroleum diesel, a characteristic associated with the molecular structure of fatty acid methyl esters (Knothe & Razon, 2021; Ndukwe & Adeyemo, 2021). Its moisture content of 0.0389% also indicates satisfactory fuel quality. The cetane number of 57.34 demonstrates good ignition quality, which can contribute to shorter ignition delay and improved combustion characteristics (Agarwal *et al.*, 2021; Verma *et al.*, 2023). Furthermore, the flash point of 94°C indicates relatively safe handling and storage, while the cloud point of -6°C suggests

favourable cold-flow characteristics under moderate low-temperature conditions. Cloud point behaviour is strongly influenced by the fatty acid composition of biodiesel (Knothe & Razon, 2021; El Marji *et al.*, 2026).

3.2 Engine Performance

Effect of Load on Fuel Consumption (FC)

Fuel consumption (FC) is the quantity of fuel required by an engine to produce the desired power output and is commonly expressed in litres per hour (L/h) or litres per kilowatt-hour (L/kWh). Figure 4.1 presents the effect of engine load on fuel consumption for pure diesel, watermelon ethyl ester blend (WOME20D80), and modified biodiesel blend WOME11D80Ace9CuO50CuSO₄50. The results show that fuel consumption increased progressively with an increase in engine load for all tested fuels. This increase is associated with the higher power demand at elevated loads, which requires a greater amount of fuel injection to maintain engine speed and generate the additional brake power needed to overcome the applied load (Zheng & Cho, 2024; Gad *et al.*, 2024). The comparison of the tested fuels indicates that the fuel consumption of neat diesel was higher than that of WOME20D80 and WOME11D80Ace9CuO50CuSO₄50 blends. The reduction in fuel consumption observed with biodiesel blends can be attributed to the presence of oxygen molecules in the ester structure, which enhances combustion efficiency by improving fuel oxidation and reducing incomplete combustion. Although biodiesel generally has a lower calorific value than conventional diesel, its oxygenated nature promotes better combustion characteristics under engine operating conditions (Bin Rashid *et al.*, 2023; Al-jabiri *et al.*, 2024). The lowest fuel consumption obtained with WOME11D80Ace9CuO50CuSO₄50 may be due to the catalytic influence of copper oxide (CuO) and copper sulphate (CuSO₄) additives. Metal-based additives improve combustion by enhancing fuel atomization, shortening ignition delay, increasing oxygen availability, and promoting faster oxidation reactions inside the combustion chamber. These effects improve the conversion of chemical energy in the fuel into useful mechanical energy, thereby reducing the quantity of fuel required for the same power output (Gad *et al.*, 2024; Tamrat *et al.*, 2024). Furthermore, the increase in fuel consumption at higher engine loads for all fuels is consistent with previous studies on biodiesel-powered compression ignition engines, which reported that increasing load increases fuel injection quantity because more energy is required to maintain engine operation and overcome external resistance. Therefore, the incorporation of watermelon ethyl ester with oxygenated compounds and metal additives demonstrates potential for improving fuel economy and engine performance compared with conventional diesel fuel (Zheng & Cho, 2024).

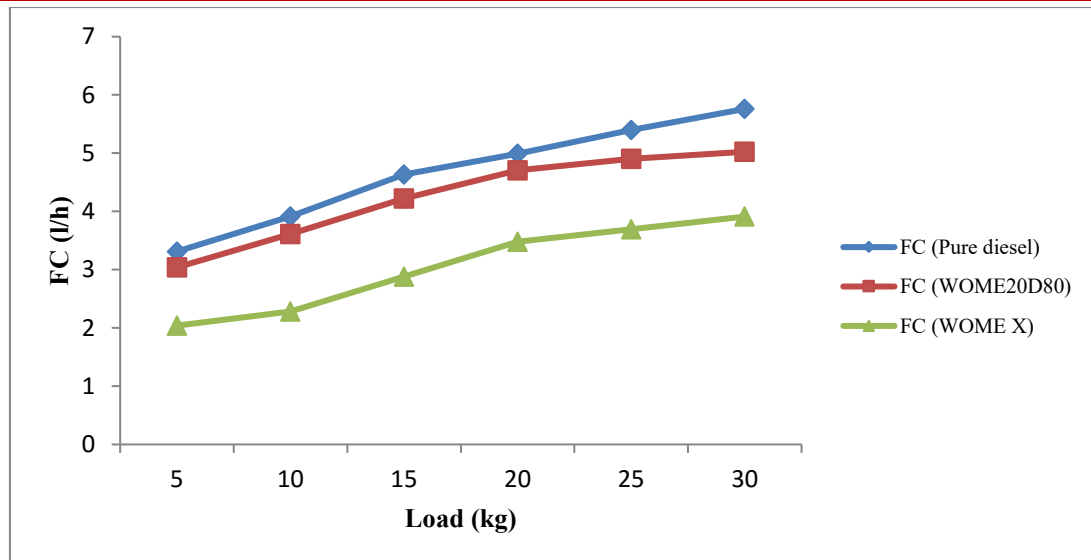


Figure 4.1: Variation of Fuel consumption with load

Effect of Load on Brake Specific Fuel Consumption (BSFC)

The variation of brake specific fuel consumption (BSFC) for pure diesel, watermelon methyl ester blend (WOME20D80), and modified biodiesel blend WOME11D80Ace9CuO50CuSO₄50 with respect to engine load is presented in Figure 4.2. BSFC represents the amount of fuel consumed by an engine to produce a unit brake power output and is an important parameter for evaluating fuel economy. The results show that BSFC decreased with increasing engine load for all tested fuels. This behaviour is due to the increase in brake power output at higher loads, which improves the utilization of fuel energy and reduces the fuel required per unit power produced (Zheng & Cho, 2024; Gad *et al.*, 2024). The BSFC values of neat diesel were higher compared with WOME20D80 and WOME11D80Ace9CuO50CuSO₄50 blends. The variation in BSFC among the fuels can be attributed to differences in physicochemical properties such as

heating value, oxygen content, viscosity, and density. Biodiesel generally has a lower calorific value than petroleum diesel; however, the presence of oxygen molecules in biodiesel enhances fuel oxidation and promotes more complete combustion, resulting in improved fuel conversion efficiency (Bin Rashid *et al.*, 2023). The lowest BSFC observed for WOME X may be associated with the catalytic activity of CuO and CuSO₄ additives. The additives improve combustion characteristics by enhancing fuel atomization, reducing ignition delay, increasing oxygen availability, and accelerating oxidation reactions within the combustion chamber. These effects improve thermal conversion efficiency and reduce the amount of fuel required to produce the same power output (Gad *et al.*, 2024; Tamrat *et al.*, 2024). Although the higher density and viscosity of biodiesel blends may negatively affect atomization, the catalytic effect of additives compensates for these limitations by improving combustion quality.

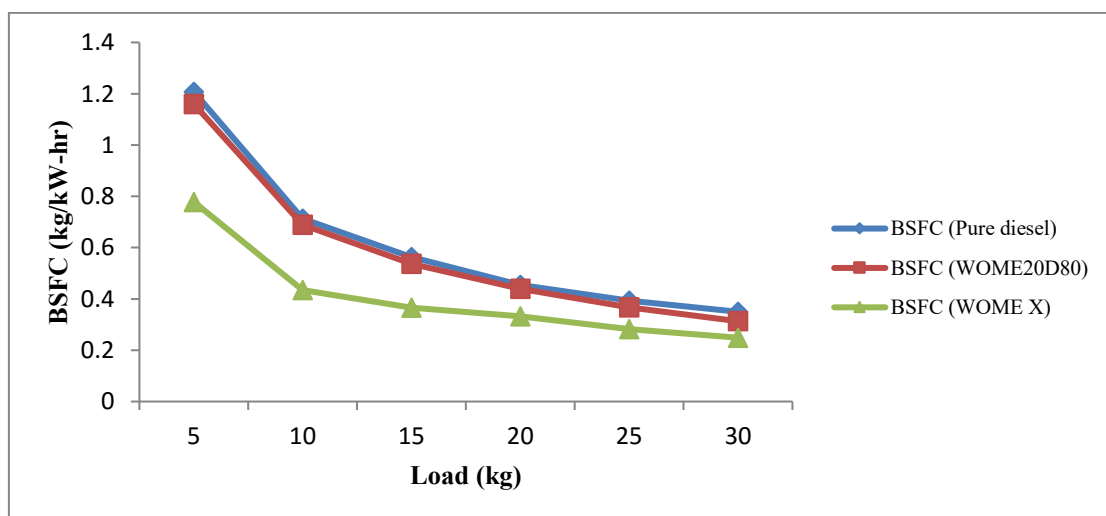


Figure 4.2: Variation of brake specific fuel consumption with load

Effect of Load on Brake Thermal Efficiency (BTE)

Brake thermal efficiency (BTE) is the ratio of brake power developed by the engine to the heat energy supplied through fuel combustion. Figure 4.3 shows the variation of BTE with engine load for pure diesel, WOME20D80, and WOME11D80Ace9CuO50CuSO₄50 fuels. The results indicate that BTE increased with increasing engine load for all tested fuels. This increase occurs because higher loads improve combustion conditions, reduce the relative effect of heat losses, and increase the proportion of fuel energy converted into useful mechanical work (Al-jabiri *et al.*, 2024). The lowest BTE was obtained with neat diesel at lower load conditions, while WOME20D80 showed a slight improvement due to the oxygenated nature of biodiesel, which enhances air–fuel mixing and

improves combustion. Biodiesel blends also possess better lubricity properties, which can improve fuel injection characteristics and combustion performance (Zheng & Cho, 2024). A significant improvement was observed when WOME11D80Ace9CuO50CuSO₄50 was used. The maximum BTE value of 37.61% at 30 kg load can be attributed to the catalytic influence of CuO and CuSO₄ additives. Metal additives enhance combustion through improved evaporation, faster oxidation reactions, increased flame stability, and better utilization of oxygen during combustion. Similar improvements in BTE using metal-based additives in biodiesel-fuelled compression ignition engines have been reported by recent studies (Gad *et al.*, 2024; Sharma *et al.*, 2024).

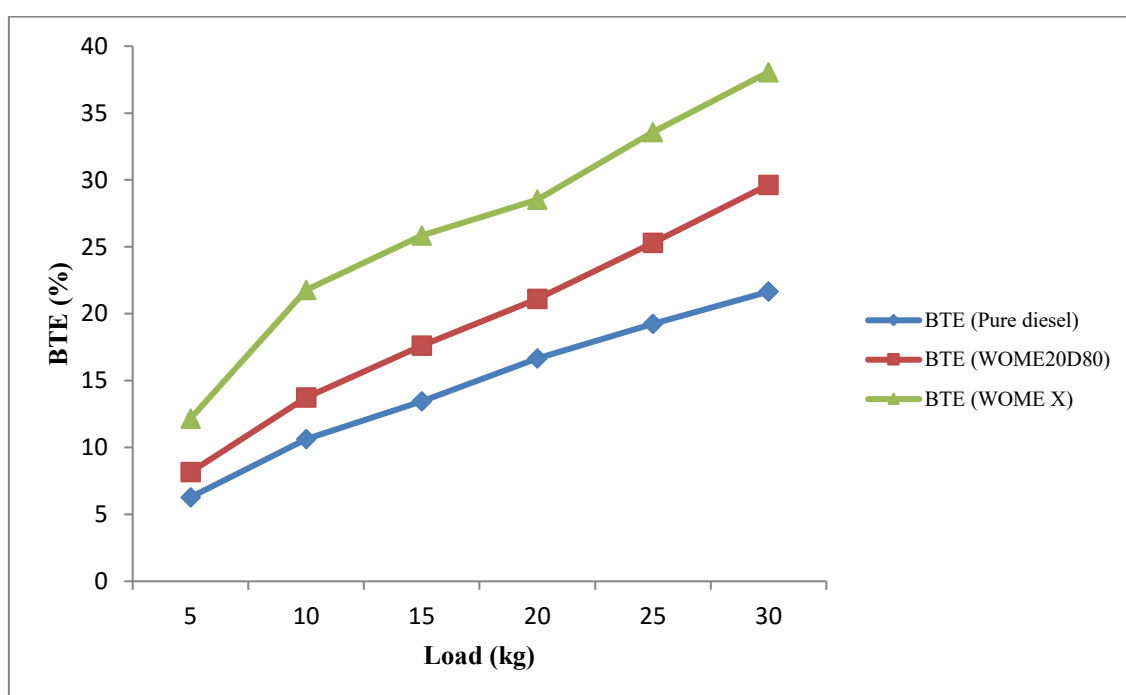


Figure 4.3: Variation of brake thermal efficiency with load

3.3 Engine Gas Emission

Effect of Load on Hydrogen Sulphide (H₂S) Emission

Hydrogen sulphide (H₂S) is a toxic sulphur-containing pollutant generated during combustion of sulphur-containing fuels. High concentrations of H₂S exposure can cause severe health effects, including respiratory irritation and loss of consciousness (Fayad *et al.*, 2022). Figure 4.4 illustrates the influence of engine load on H₂S emission from neat diesel, WOME20D80, and WOME11D80Ace9CuO30CuSO₄50 fuels. The results show that H₂S emission increased with increasing engine load for all tested fuels. This increase is associated with higher fuel consumption and greater

combustion of sulphur-containing compounds at higher loads. Pure diesel produced the highest H₂S emission compared with biodiesel blends due to its higher sulphur content. The reduction in H₂S emission from WOME20D80 is attributed to the oxygen content of biodiesel, which promotes oxidation of sulphur compounds into sulphur dioxide (SO₂) rather than hydrogen sulphide. The lowest H₂S emissions obtained from WOME11D80Ace9CuO30CuSO₄50 are linked to the catalytic effect of additives, which improve combustion efficiency and reduce incomplete sulphur reactions (Bin Rashid *et al.*, 2023; Gad *et al.*, 2024).

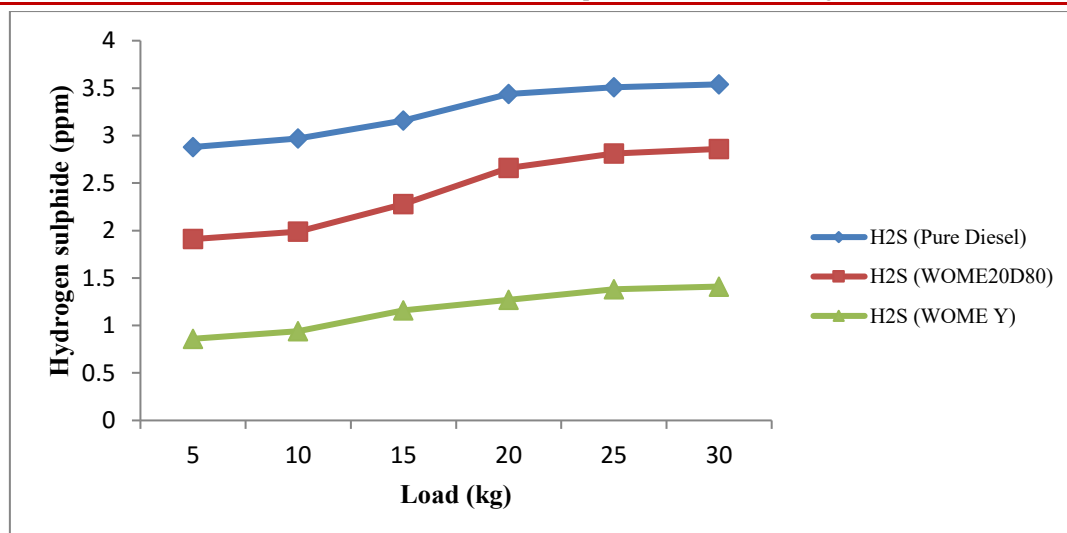


Figure 4.4: Variation of hydrogen sulphide emission with load

Effect of Load on Nitrogen Dioxide (NO_2) Emission

Nitrogen dioxide formation in compression ignition engines depends mainly on combustion temperature, oxygen availability, and residence time of combustion gases. Figure 4.5 presents the variation of NO_2 emission with engine load. The results indicate that NO_2 emissions increased with increasing load for pure diesel and biodiesel blends. This occurs because higher loads increase fuel injection quantity and combustion temperature, which promotes oxidation of atmospheric nitrogen (Al-jabiri *et al.*, 2024). WOME20D80 produced slightly higher NO_2 emissions than neat diesel because

biodiesel contains chemically bound oxygen, which improves combustion and increases local oxygen concentration, favouring NO_2 formation. However, the addition of oxygenated compound, CuO and CuSO_4 additives significantly reduced NO_2 emissions. This reduction may be attributed to improved combustion control, shortened ignition delay, and catalytic reactions that reduce nitrogen-containing radicals responsible for NO_2 formation (Sharma *et al.*, 2024).

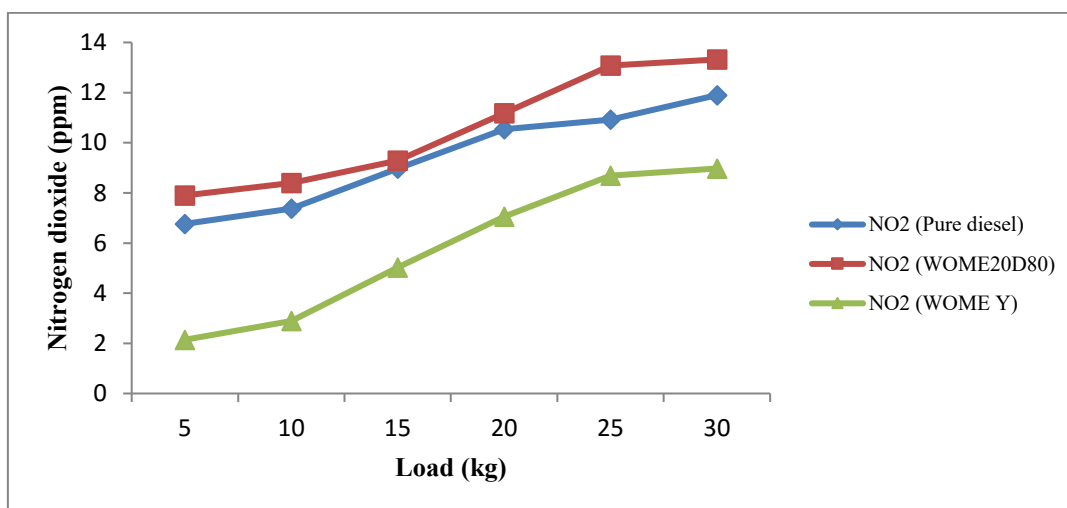


Figure 4.5: Variation of nitrogen dioxide with load

Effect of Load on Carbon Monoxide (CO) Emission

CO is an indicator of incomplete combustion and is influenced by fuel properties, air–fuel ratio, atomization, combustion temperature and engine load. Figure 4.5 shows that CO increased with increasing load for all fuels. This may be due to the greater quantity of fuel supplied at higher loads, which can increase locally fuel-rich regions and limit oxygen availability. Pure diesel produced higher CO emissions than

WOME20D80. The lower CO from WOME20D80 may be attributed to the chemically bound oxygen in biodiesel, which supports oxidation of CO to CO_2 . Similar reductions in CO from biodiesel blends have been reported by Loo *et al.*, (2021). WOME11D80Ace9CuO30CuSO₄50 produced the lowest CO emissions. The lower CO emission may result from the combined effects of biodiesel-bound oxygen and the catalytic characteristics of the metal-based

additives. Nanoparticles can influence atomization, evaporation, fuel–air mixing and oxidation reactions (Haq *et al.*,2024). Studies involving CuO-containing biodiesel have also reported reductions in CO emissions (Garugubilli *et al.*,2024; Muniyappan & Krishnaiah,

2024). Overall, CO increased with engine load, while WOME20D80 and particularly WOME11D80Ace9CuO30CuSO₄50 produced lower CO emissions than pure diesel.

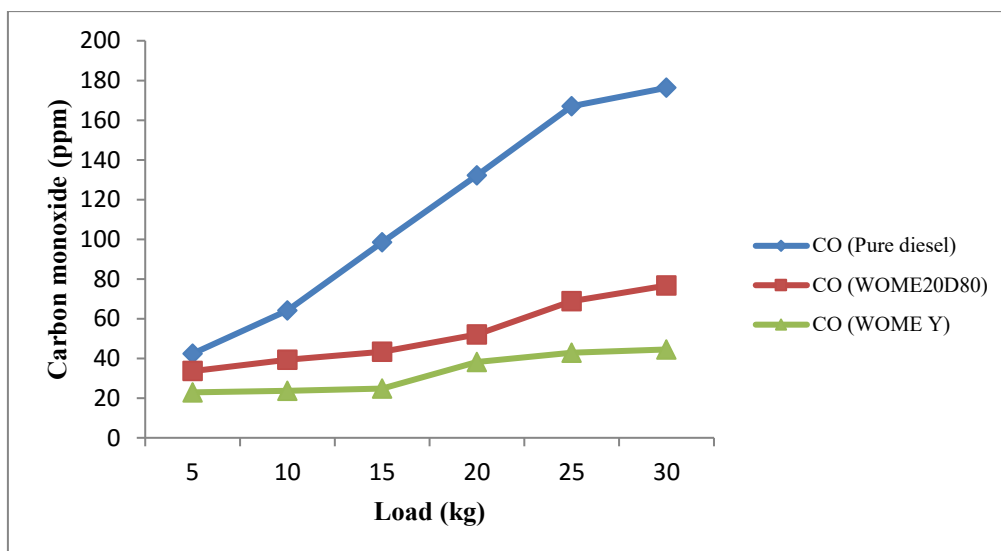


Figure 4.6: Variation of carbon monoxide with load

Effects of Load on Exhaust Gas Temperature (EGT)

EGT indicates the thermal behaviour of the engine and is influenced by load, fuel properties, combustion characteristics and heat transfer. Figure 4.7 presents the variation of exhaust gas temperature with engine load. Exhaust temperature increased with increasing load for all fuels because higher loads require more fuel injection, resulting in increased heat release during combustion. Pure diesel recorded the highest exhaust temperature, while WOME11D80Ace9CuO30CuSO₄50 produced the lowest values. The reduction in exhaust temperature with

additive-modified biodiesel can be attributed to improved combustion efficiency, reduced heat losses through exhaust gases, and better conversion of fuel energy into mechanical output. Nanoparticle additives have been reported to influence spray atomization, improve combustion characteristics and reduce unburnt fuel energy leaving through exhaust gases (Gad *et al.*,2024; Haq *et al.*,2024; Muniyappan & Krishnaiah, 2024). Overall, EGT increased with load, but WOME20D80 and particularly WOME20D80 + additives produced lower exhaust temperatures than pure diesel.

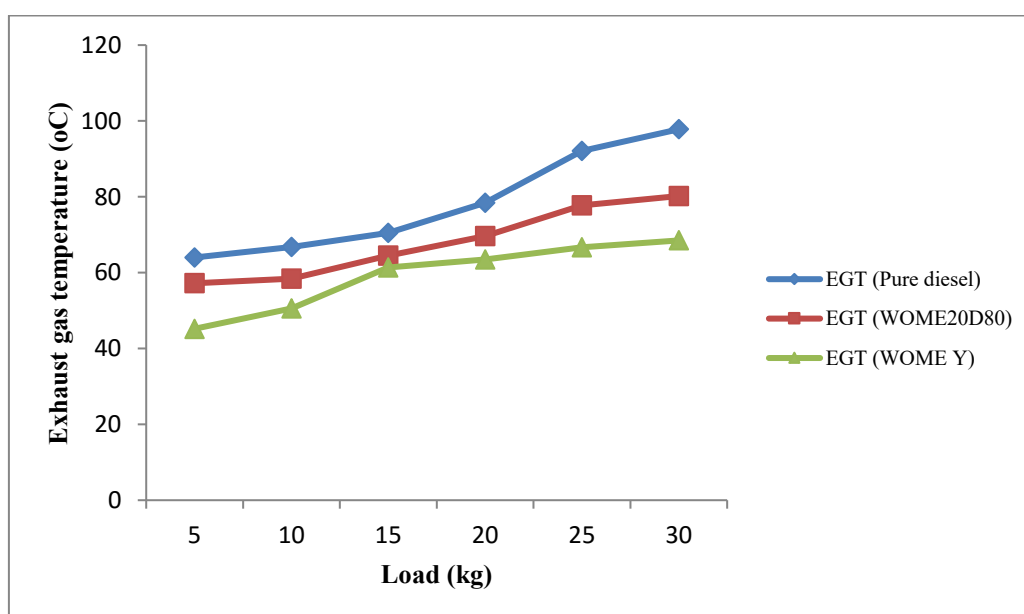


Figure 4.7: Variation of exhaust gas temperature with load

Effect of Load on Methane (CH_4) Emission

Methane (CH_4) is an unburned hydrocarbon that can result from incomplete fuel oxidation. Its formation is influenced by fuel composition, air–fuel mixing, ignition characteristics, combustion temperature and engine load. Figure 4.8 shows that CH_4 emission decreased progressively with increasing load for all fuels. The decrease may be associated with improved combustion conditions and higher combustion temperatures at increased loads, which promote oxidation of unburned hydrocarbons. Pure diesel produced the highest CH_4 emissions, whereas WOME20D80 recorded substantially lower values. The lower CH_4 emission may be related partly to the fuel-bound oxygen in biodiesel, which supports oxidation of incompletely burned hydrocarbons (Loo *et al.*,2021).

Further reductions were obtained with WOME11D80Ace9CuO30CuSO₄50. The effect may be associated with the combined influence of biodiesel-bound oxygen and the catalytic characteristics of the metal-based additives. CuO-containing biodiesel fuels have been reported to improve combustion and reduce unburned hydrocarbon emissions (Muniyappan & Krishnaiah, 2024). Nanoparticles can also influence fuel atomization, evaporation and fuel–air mixing (Haq *et al.*,2024). Overall, CH_4 decreased with increasing engine load, while WOME20D80 produced lower emissions than pure diesel and the additive-containing blend produced further reductions. The observed trend is likely the result of interacting effects involving oxygen availability, combustion temperature, spray development and oxidation processes.

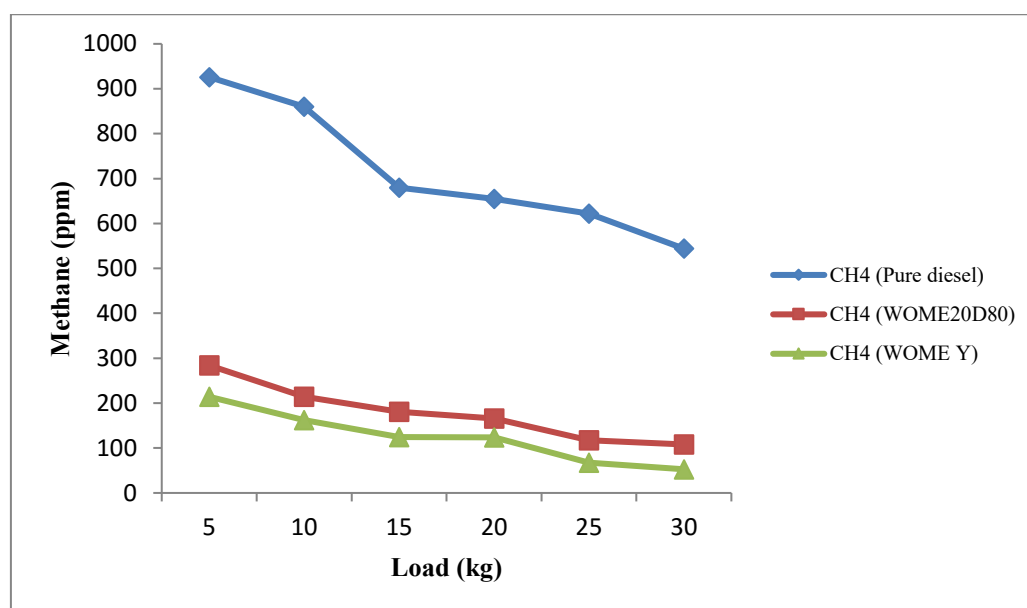


Figure 4.8: Variation of methane emissions with load

4. CONCLUSION

This study successfully produced watermelon seed oil methyl ester (WOME) via transesterification and evaluated its performance and emission characteristics when blended with petroleum diesel and metal/oxygenated additives. The empirical findings lead to the following key conclusions: Optimal Blends: The WOME11D80Ace9CuO50CuSO₄50 blend yielded the best overall engine performance properties. Emission Reductions: The WOME11D80Ace9CuO30CuSO₄50 blend achieved the lowest overall emissions, including a minimum methane (CH_4) emission of 52.7 ppm. Fuel Consumption: Fuel consumption increased across all samples under higher engine loads due to increased power demands.

Efficiency Milestones: At a 30 kg load, the lowest Brake Specific Fuel Consumption (BSFC) recorded was 0.2438 kg/kW-hr, while the highest Brake Thermal Efficiency (BTE) reached 38.06%. Load

Dynamics: Increasing the engine load led to higher H_2S , NO_2 , CO, and Exhaust Gas Temperature (EGT), but successfully reduced CH_4 emissions. In summary, combining copper(II) oxide, copper(II) sulphate, and acetoacetic ester as additives significantly optimizes biodiesel performance. This formulation effectively lowers fuel consumption, decreases harmful emissions (NO_2 , CO, H_2S , CH_4), reduces exhaust gas temperatures, and improves brake thermal efficiency across varying engine loads.

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