Journal of Thermal Analysis and Calorimetry
https://doi.org/10.1007/s10973-025-14034-w

Experimental assessment of hybrid binary and ternary fuel blends on CI engine performance, emissions, and combustion characteristics

Aisha F. Fareed[1,2] · A. S. El-Shafay[3,6] · M. S. Gad[4] · Ümit Ağbulut[5,7]

Received: 17 October 2024 / Accepted: 17 January 2025
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Abstract

The increased density and viscosity of crude biodiesel derived from palm and waste cooking oils (WCO) present problems such as vaporization and atomization. A hybrid biodiesel mixture ensures to have better calorific values, lowest density, and viscosity. Biodiesel fuels were synthesized using the esterification and transesterification of palm and WCO, and it was blended in proportions of 10 and 20% with pure diesel. Combustion, performance, and emissions of diesel engine fuelling with hybrid biodiesel blends at load variation and rated speed of 3000 rpm were evaluated. Thermal efficiency was decreased with the increasing ratio of methyl ester in mixtures, whereas specific fuel consumption rose due to the diminished calorific value of methyl ester. In comparison with diesel fuel, biodiesel from palm (10%), waste cooking oil (10%), blended WCO (10%) + palm (10%), waste cooking oil (20%), and palm oil (20%) exhibited the most significant increases in specific fuel consumption, recorded at 1.5, 3.5, 6, 7, and 9%, respectively. Nonetheless, there were concomitant reductions in thermal efficiency of 2, 4, 5.5, 6.5, and 10%. Maximum reductions in smoke concentration for P10, W10, W10 + P10, W20, and P20 were 5, 7, 9, 10, and 12%, respectively. Maximum cylinder pressures were reduced by 1, 1.8, 2.8, 3.5, and 4%, on average, although the peak HRR regarding diesel fuel at maximum output power was dropped by 1, 2, 3.2, 4, and 4.5%. Hybridization of feedstocks with diverse properties improves performance, combustion, and emissions of diesel engines run by combinations of 10% palm and 10% WCO hybrid biodiesel. As an alternative fuel, hybrid palm and waste cooking methyl esters can be used to increase performance and combustion while lowering exhaust emissions.

Keywords Waste cooking oil · Palm oil · Hybrid biodiesel · Performance · Emissions · Combustion characteristics

Abbreviations

BSFC	Brake-specific fuel consumption, kg kWh^{-1}
BTDC	Before top dead center
BTE	Brake thermal efficiency, %
CO	Carbon mono-oxide emission, ppm
D100	Pure diesel fuel
EGT	Exhaust gas temperature, °C
HC	HC emission, ppm
HRR	Net heat release rate, Joule/Degree
NOx	Nitrogen oxides concentrations, ppm
P10	Palm biodiesel of 10% + diesel fuel of 90%
P20	Diesel fuel of 80% + palm biodiesel of 90%
P_{cy}	In-cylinder pressure, bar
W10	WCO biodiesel of 10% + diesel fuel of 90%

✉ A. S. El-Shafay
a.abdou@psau.edu.sa

✉ Ümit Ağbulut
umit.agbulut@yildiz.edu.tr

[1] Department of Electrical Engineering, College of Engineering, Prince Sattam Bin Abdulaziz University, 11942 Al Kharj, Saudi Arabia

[2] Department of Basic Engineering Sciences, Benha Faculty of Engineering, Benha University, Benha, Egypt

[3] Department of Mechanical Engineering, College of Engineering in Al-Kharj, Prince Sattam bin Abdulaziz University, Al-Kharj 11942, Saudi Arabia

[4] Mechanical Engineering Department, Faculty of Engineering, Fayoum University, Fayoum, Egypt

[5] Department of Mechanical Engineering, Mechanical Engineering Faculty, Yildiz Technical University, 34349 Istanbul, Turkey

[6] Mechanical Power Engineering Department, Faculty of Engineering, Mansoura University, 35516, Mansoura, Egypt

[7] Department of Technical Sciences, Western Caspian University, Baku, Azerbaijan

Published online: 19 February 2025

W20	Diesel fuel of 80% + WCO biodiesel of 20%
W10 + P10	Palm biodiesel of 10% + WCO biodiesel of 10% + diesel fuel of 80

Introduction

Diesel engines are effective and esteemed for industrial, transportation, agriculture, and power owing to their operational attributes, elevated compression ratio, and enhanced thermal efficiency. The probability of fossil fuel depletion shortly has escalated owing to the excessive use of diesel fuel driven by fast industrial expansion and unrestrained automotive usage. Fossil fuel use rose by 51% in the two decades before 2015, and it is projected to increase by an additional 18% by 2035 [1]. Fossil fuels are limited and in danger of running out due to their massive consumption. Furthermore, dangerous pollutants like greenhouse gases that are connected to fuel use have a negative influence on the ecosystem. Consequently, this is the main driving force behind the researchers' quest for alternative fuel sources, which seeks to create efficient, clean fuel sources to solve a variety of problems. The issue of fossil fuel depletion due to escalating use, with environmental degradation from detrimental emissions, necessitates the implementation of suitable alternative fuels [2]. Since they are frequently produced using renewable resources like organic waste, algae, and plant biomass, they are inherently more environmentally friendly. These fuel sources can reduce their harmful impacts on air quality and human health by reducing particulate matter, carbon dioxide emissions, and other harmful pollutants [3].

The global yearly energy demand is projected to surpass 12 billion tons of crude oil, resulting in emissions of around 39.5 Gt of carbon dioxide, estimated increase to 75 Gt shortly due to escalating energy consumption [4]. In recent decades, biodiesel has emerged as a viable alternative to petroleum diesel in the industrial and automotive sectors, owing to its affordability and widespread availability. Biodiesels derived from various feedstock generations have shown efficacy as a substitute for petroleum diesel. Cottonseed, sunflower, soybean, palm oil, rapeseed, and other edible oils used in biodiesel production exemplify first-generation feedstocks. Methyl ester was generally utilized as a fuel to achieve equivalent performance with lower exhaust emissions while maintaining the integrity of the engine . Sunflower, waste coconut oil, palm oil, and other edible and non-edible oils were used to make biodiesel, which was subsequently converted into hybrid biofuel with better physical properties [5]. In comparison with diesel fuel, biodiesel is denser, more viscous, and has a lower calorific value. In cold climates, these characteristics cause issues with atomization, vaporization, and air–fuel mixing [5]. Filter blocking and injector coking are the results of these problems. Combining biodiesels from several feedstocks enhances their chemical and physical characteristics compared to pure biodiesels [6].

Similarly, biodiesel usage along with conventional diesel fuel produces arise in NOx quantity while emitting far fewer pollutants from a diesel engine, such as HC and CO . When compared to regular diesel, biodiesel made from cottonseed oil had acceptable performance and emissions [7]. Using first-generation feedstocks to make biodiesel has several drawbacks since they are intricately connected to the human food supply chain [8]. The biodiesel productions from second-generation feedstocks are mostly non-edible oils such as mahua indicia, neem, castor, karanja, jatropha, jojoba, and rubber seed oil [9]. Biofuel containing 20% ratio of karanja methyl ester emits less HC and CO emissions [10]. Additionally, it may be thought that the biofuel composition with 20% karanja oil methyl ester is the most ideal for dual-fuel engine [11]. Combining alkyl esters from several sources might be a practical strategy to boost engine output [12]. Combining different oils may lead to better physicochemical properties, which will increase the mixture of biodiesel's fuel characteristics [13]. Additionally, the right combination of oils provides an optimum fuel characteristics, and can decrease viscosity, density, and acid value, which will cut down on the time and cost of esterification [14]. An analysis was conducted to compare the benefits and drawbacks of utilizing single-fuel blended biodiesel against hybrid-fuel mixed biodiesel while accounting for the emissions and performance of diesel engines [15]. By adding 10% methyl ester to pure diesel, hybrid-blended fuel derived from palm and jatropha oil produced 4.65% higher output power and 17.7% less CO emissions [14]. Increase of the methyl ester percentage drops the thermal efficiency[16]. Dual-mixed biodiesel with 10% mahua and rapeseed oil has a considerable impact on diesel engine emissions, producing 20.6, 8.5, and 6.9% less CO, HC and smoke, respectively [17]. Dual-mixed methyl esters with varying concentrations were shown to be preferred for use as engine fuel, with the mixture containing 15% of each biodiesel component exhibiting superior attributes over other compositions [19]. A dual biodiesel blend produces higher BTE, lower BSFC, and about fewer emissions by blending waste cooking oil with animal fat oil in different proportions [18]. Thefore, it is possible to conclude that better engine performance for a diesel engine was achieved using a hybrid fuel combination . As a result, using dual biodiesel blends produced from various feedstocks may intensely increase and improve engine performance and reduce emissions [20].

A variety of materials including WCO, animal fats like lard, and edible, and inedible oils are utilized to make alternative fuels like methyl ester [21]. In relation to pure diesel fuels, methyl ester of waste cooking oil has lower sulfur

concentration, lower aromatic characteristics, and greater oxygen content, all of which result in lower percentages of CO and HC [30]. Castor seeds typically have 40–55%t oil content, which is substantially higher than the oil content of soybeans (15–20%), sunflowers (25–35%), rapeseeds (38–46%), and palms (30–60%). Characteristics of 10% diesel mixture (B10) and pure castor oil biodiesel were investigated, B10 mixture agreed with standards, kinematic viscosity and distillation temperature of castor oil methyl ester (COME) adhered to ASTM D6751 biodiesel specifications [22]. Due to its outstanding lubricating characteristics of the engine, COME has proven to be an ideal alternative to diesel. The research analyzed the diesel engine performance working on ternary blends of diesel and methyl ester (B5, B10, and B20) about conventional diesel fuel [33]. At 1500 rpm, mixed fuels were demonstrated to perform comparable to pure diesel. The performance characteristics, which varied from 1000 to 2400 rpm, were calculated using the engine speed variation [34]. The study indicates that the ratio increase of castor biodiesel in the mixture produced a small decline in output power and fuel consumption increase. Conversely, NOx concentrations were increased, while HC_2 and carbon monoxide releases were declined with the use of castor methyl ester. B25 is the recommended substitute for CI engines [35]. B10 outperformed the other two combinations for BTE at peak engine brake power. Compared to diesel fuel, the combination' COME produced lower emissions of CO, NOx, and HC [35]. The study examined essential performance parameters as the variation from 1000 to 2400 rpm for engine speed. The incorporation of castor oil biofuel led to the NOx levels increases and decreases in carbon dioxide and monoxide emissions. Research reveals that B25, with 25% biodiesel, is the optimal blend for diesel engines [35]. In comparison with other fuels, the B10 blend demonstrated superior brake thermal efficiency at full brake power. Concentrations of hydrocarbons and CO were decreased with the incorporation of methyl ester into diesel fuel. Comparable studies demonstrate that fuels with a mixture of methyl ester and diesel have elevated rates of heat release and peak cylinder pressure. The flash point, density, viscosity, and calorific value of B20 were comparable to those of diesel, leading to enhanced engine performance [40]. The incorporation of methyl ester with diesel in engines is subject to certain limitations. The drawbacks include elevated density, viscosity, inadequate atomization of fuel, decreased pour point,lower cloud point, piston ring adhesion, increased NOx emissions, and challenges with cold starting [41].

o create a B20 blend, diesel was mixed with Pongamia Pinnata methyl ester, which was made by transesterification. Graphene oxide nanoparticles at concentrations of 40, 80, and 100 mg/liter were added to B20, and 3 vol.% diethyl ether was added as a supplement. When 100 ppm GO nanoparticles and 5 vol.% diethyl ether were added, brake-specific fuel consumption was decreased by 10.71% and brake thermal efficiency was increased by 19.7% at maximum loading. CO, HC, and smoke emissions were significantly reduced by 47.9, 70.3, and 23.8%, respectively [36]. Diesel engine performance using Ricinus communis biodiesel, diesel (80%), and their mixtures with additives made of strontium-zinc oxide nanoparticles. In mass fractions of 30, 60, and 90 ppm, Sr@ZnO nanoparticles were mixed with RCME20-diesel fuel blend. While NOx slightly rose for all nanofuel blends, engine parameters including BTE, HRR, and cylinder pressure were increased by 20.83%, 24.35%, and 9.55%, but BSFC, ID, CD, smoke, CO, HC, and CO_2 were decreased by 20.07%, 20.64%, 14.5%, 27.90%, 47.63%, 26.81%, and 34.9%, respectively [37]. Palm biodiesel of 30% and diesel were combined with 10% dimethyl carbonate (DMC). GNPs at three distinct concentrations (40, 80, and 120 ppm) were added to these mixtures. In comparison with all other tested blends, B30GNP40DMC10 had the highest BTE of 22.80% and the highest BSFC decrease of 5.05%. B30DMC10 showed a decrease in HC (25%) and CO (4.41%), while B30GNP40DMC10 showed a decrease in NOx of 3.65%. As a result, the combined GNP and DMC demonstrated great potential for use in diesel engine operation [38].

The primary aim of this work is to produce an alternative fuel including methyl esters blends derived from waste cooking and palm oils to evaluate their influences on the performance, combustion, and emissions of diesel engines. Other references were focused on using single or multi-biodiesels from different feedstocks, but there is a gap of using hybrid biodiesel from different feedstocks which is not covered. The study sought to improve the chemical and physical characteristics of biodiesel by amalgamating it with substitute feedstocks, namely palm oil and WCO, to create a hybrid methyl ester. The disposal of WCO is detrimental to both environmental integrity and human health. WCO should be transformed into energy that is advantageous for both the environment and the economy. The literature does not discuss the blending of diverse biodiesel types derived from distinct edible and inedible feedstocks. The vaporization and atomization of crude methyl ester obtained from palm oil and waste cooking oil may be impeded by its high density, viscosity, and diminished calorific values. Utilizing biodiesel is a dependable and beneficial practice for ecological sustainability. Consequently, using pure biodiesel in cold climates may restrict its exclusive use in diesel engines. Pure biodiesel may damage engine hardware and obstruct nozzles and filters because of its heightened viscosity and density at cold temperatures. Blending several kinds of methyl esters might make them more advantageous while lessening their disadvantages. By blending several feedstocks, biodiesel can have more benefits and fewer downsides. After the

preparation of biodiesels from palm oil and WCO, diesel was combined with them at volume percentages of 10 and 20%. Analyzing these mixtures' performance, combustion, and emissions characteristics at constant speed under various loads was the goal. The investigation focused on factors such as smoke opacity, carbon monoxide, hydrocarbons, and nitrogen oxides (NOx), the temperature of exhaust gases (EGT), brake-specific fuel use (BSFC), and brake thermal efficiency (BTE). Net heat release rate and in-cylinder pressure were evaluated to address the research gap regarding the use of methyl ester mixtures derived from WCO and palm biodiesels for improved engine performance and combustion. Palm and WCO oils were selected as feedstocks due to their complementing properties and potential advantages in the making of methyl ester. Palm oil has a high energy content and outstanding combustion properties due to its favorable fatty acid makeup. It is also abundantly available. However, used cooking oil provides a cheap and sustainable feedstock that lessens the problems associated with disposing of garbage. It is less expensive to produce, but because of frequent heating and deterioration, it frequently has inconsistent qualities. The benefits of both feedstocks are combined when palm oil and used cooking oil are hybridized. This method can increase the fuel's characteristics, increase biodiesel's sustainability, and reduce overall production costs. Increased oxidation stability, improved cold flow properties, and enhanced combustion efficiency can result from the balanced blend of the saturated and unsaturated fatty acids found in biodiesel palm oil and biodiesel WCO. The study intends to show that hybridization can provide a feasible route to manufacture high-quality biodiesel that satisfies both economic and environmental goals by examining the synergistic impacts of these two oils.

Methodology

Tested fuel preparation

To produce biodiesel from palm oil, it should undergo pretreatment with preheating to 90 °C for 15 min to eliminate moisture, followed by centrifugation and filtration to remove pollutants and gums, and finally washing with neutral pH water. Upon completion of the pretreatment esterification process, the distillate of palm fatty acid is amalgamated with a mixture of ethanol and sulfuric acid. To eliminate moisture, palm fatty acid is preheated to the temperature of 80 °C5. The combination of reactants consists of 5 mL of H_2SO_4, one liter of palm oil, and 250 mL of ethanol. The response time is 60 min. Free fatty acid (FFA) was then analyzed. Transesterification base-catalyzed yielding monoalkyl esters and glycerin should be conducted when the FFA concentration is below 2%. Esterified oil was combined with 250 mL of ethanol and five grams of sodium hydroxide catalyst. The temperature of oil between 65 and 70 °C was adjusted. Oil was amalgamated with the ethanol and catalyst mixture and thereafter stirred for 30 min time. FFA concentration of the mixture must be below 0.5%. The mixture was agitated rapidly for three hours at 700 rpm. After that, the mixture was placed in a separating funnel and left for 12 h to settle. Glycerol and other contaminants were extracted from the lower layer, resulting in the formation of a palm ethyl ester comprising alcohol and water in the top layer. To remove the glycerin from the methyl ester and balance the pH of the water, three or four washings were needed. It was subsequently amalgamated to eliminate the glycerol and any other contaminants. To get pure palm ethyl ester, a rotary evaporator was employed to decrease the content of moisture. The reference fuel used was Diesel No. 2. Biodiesel blends consist of varying volumetric ratios of diesel and palm biodiesel. B10 and B20 denote 10 and 20% concentrations of palm methyl ester in petroleum diesel, respectively.

WCO was supplied from hotels and restaurants. To remove the contaminants from the oil, filtration process was utilized. To lower the moisture level, the oil was heated upto 70 °C. NaOH catalyst was used to combine the oil and methanol, and the mixture was constantly agitated. When methanol and oil are combined to make methyl ester, the optimal molar ratio is 6:1. To finish the transesterification process, the blend should be pushed through a separating funnel for 12 hrs. The biodiesel was purified with water and the glycerol was taken out in order to get rid of the unreacted methoxide. B20 and B10 are methyl ester and crude diesel mixtures with a volume ratio of 20 and 10%, respectively. The diesel fuel and biodiesel were combined precisely in volume percentages and stirred with a magnetic stirrer at a controlled temperature to verify the homogeneity of the mixtures. The mixtures were blended and then given time to settle in order to prevent phase separation. A number of important factors were taken into consideration while choosing the biodiesel mixing percentages in order to enhance emissions, combustion characteristics, and engine performance. In general, diesel and biodiesel at low mixing ratios such as 10 and 20% have been shown to work well with traditional diesel engines. Our discovery has practical significance as these ratios may be employed in current engines without requiring considerable changes. B10 and B20 are known to improve thermal efficiency and reduce specific fuel consumption at lower blending ratios because they resemble diesel oil in some ways. Mixtures containing 10 and 20% biodiesel have been shown to significantly reduce concentrations of CO, HC, and smoke because the oxygenated nature of the fuel promotes more complete combustion. Engine efficiency and fuel atomization may be affected by increased viscosity and lower calorific value resulting from greater blend ratios. In order to maintain the blended fuel's

characteristics close to those of regular diesel, B10 and B20 were used. A lot of nations have made B10 and B20 the industry standard blend levels for biodiesel, in order to comply with environmental laws and support renewable energy sources. By choosing these percentages, our research complies with legal requirements and industry norms, guaranteeing the applicability of our conclusions. The selection of 10 and 20% biodiesel blends was led by these parameters in order to ensure that the blends are suitable for actual applications and to thoroughly assess their impacts on engine emissions, performance, and combustion. Conventional diesel has a superior heating value compared to biodiesel derived from palm oil and WCO. Palm and WCO biodiesels exhibit elevated cetane numbers, densities, viscosities, and flash points compared to diesel oil. The challenges of atomization and vaporization arise from the elevated density and viscosity of biodiesel. In cold climates, these problems lead to fuel filter obstruction and injector carbon buildup. The decreased energy production results from the inferior heating value of biodiesel relative to crude diesel. Methyl ester's elevated cetane number in diesel oil, results in reduced cylinder pressure, decreased heat release, shortened ignition delay, and worse combustion. The hybridization of two biodiesels derived from distinct feedstocks, namely palm and waste cooking oils, enhances the attributes of P20, W20, palm, and WCO biodiesel, including density, calorific value, viscosity, flash point, and cetane number. Enhancements in physical and chemical properties result in improved cylinder pressure, heat release, decreased concentrations of CO, HC, and smoke, declined BSFC, and improved BTE.

A strict mixing procedure was used to guarantee and demonstrate consistent mixing across various biodiesel blends. To attain homogeneity, the diesel fuel and biodiesel were mixed in exact volume percentages and agitated with a magnetic stirrer with constant stirring for 30 min at 600 rpm to achieve even homogeneity. Blends of biodiesel up to 20% of volume have close density and viscosity comparable to diesel fuel. The density and viscosity of diesel fuel and biodiesel differ slightly. In order to avoid phase separation, the mixtures were allowed to stabilize after mixing. Homogeneous mixing was demonstrated by consistent density and viscosity values across samples. In order to provide accurate data for performance, combustion, and emissions studies, it was made sure that the biodiesel blends were blended consistently.

Table 1 shows the physical and chemical characteristics of methyl ester combinations. In comparison with diesel fuel, biodiesel and its blends have higher specific fuel consumption, higher exhaust gas temperatures, and inferior thermal efficiency due to their high viscosity, density, and low calorific value. When compared to crude diesel, the characteristics of biodiesel resulted in lower cylinder pressure and heat release. Methyl ester's higher cetane number than diesel has a negative impact on combustion properties, while CO, CO_2, HC, and smoke levels decreases due to lower carbon and higher oxygen contents emissions of nitrogen oxides rise. Pure biodiesel can harm engine parts and clog filters and injector nozzles because it grows denser and more viscous in colder conditions. The blend W10 + P10 was demonstrated to have better and superior qualities in terms of density, calorific value, cetane number, and viscosity with regard to palm, WCO biodiesel, W20, and P20. The goal of hybridization was to blend the benefits of various biodiesels while minimizing their drawbacks. Combining hybrid biodiesel can result in simultaneous improvements in density, viscosity, cetane number, vaporization, and cold properties.

Experimental test rig

The four-stroke, twin-cylinder, direct-injection, water-cooled referred to as the CI engine, is used for testing purposes. The diesel engine can yield the highest torque of 26 N.m at 3000 rpm. The stroke is 62 mm, and the diameter is 72 mm. Cylinder pressure was monitored using a water-cooled piezoelectric pressure transducer, which can measure pressure up to 250 bar and has a sensitivity of 16.5 pc/bar and an accuracy level of 1.118%. In order to reduce signal delay and alleviate pipe connection passage resonance, the pressure

Table 1 Characteristics of waste cooking oil and palm methyl esters

Properties	Method	Diesel Oil	WCO Biodiesel	Palm Biodiesel	W20	P20	W10 + P10
Density at 15.56 °C, kg m^{-3}	ASTM D-4052	827	865	875	842	851	834
Flash point/ °C	ASTM D-93	72	140	155	85	97	81
Cetane number	ASTM D-13	46	51	52	48	50	47
Lower heating value/ kJ kg^{-1}	ASTM D-224	42,100	39,400	38,700	41,700	40,800	41,900
Kinematic viscosity at 40 °C/ CSt	ASTM D-445	2.1	4	5	3	3.2	2.7
Carbon content/ %	–	86	76	77	–	–	–
Pour point/ °C	ASTM-D6751	10	− 15	− 16	–	–	–
Cloud point/ °C	ASTM-D2500	1	− 2	− 3	–	–	–

transducer was flush-attached to the cylinder head and linked to a charge amplifier. A proximity switch was mounted on the engine's output shaft controlled the piston position. Cylinder pressure was averaged over 125 engine cycles to guarantee data accuracy. Personal computer software with data acquisition card allowed for high-speed data collecting and analysis. The smoke is quantified using an OM-100 opacity meter, which has a resolution of 0.1% and a measurement range of 0–100%. An examination of exhaust concentrations is conducted using KOEN exhaust gas analyzer (model: KEG-500). The NOx (0–5000 ppm, accuracy 1 ppm), HC (0–9999 ppm, accuracy 1 ppm), and CO (0–10%, accuracy 1%) exhaust emissions were measured. Figures 1 and 2 show the photographic view and schematic diagram of the experimental rig, respectively. EGT was assessed using K-type thermocouples, which possess an accuracy of 1 °C. The quantity of utilized fuel was assessed using a glass burette with a capacity of 0–100 mL and a resolution of 1 mL. The engine's speed is ascertained via the use of a digital tachometer. Performance measures for brake-specific fuel consumption, brake thermal efficiency, and exhaust gas temperature were assessed. Smoke, hydrocarbons, nitrogen oxides, and



Fig. 1 Photographic view of the test rig

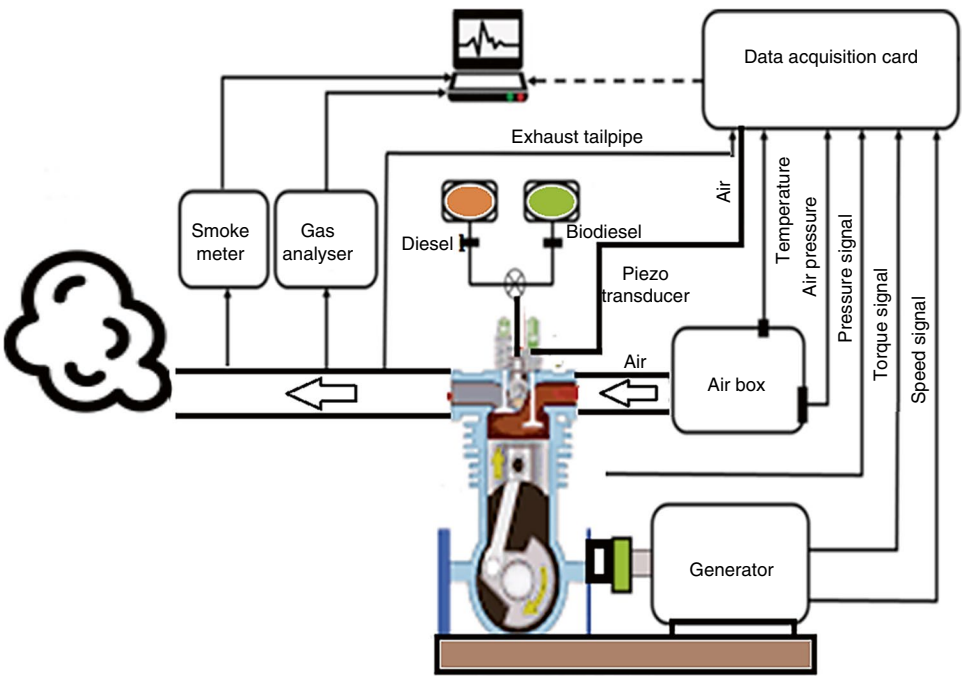


Fig. 2 Test rig schematic diagram

carbon monoxide emissions were evaluated. Even when the load fluctuated during the testing from zero to maximum, the designated speed of 1500 rpm remained constant. After warming up with pure diesel fuel, the engine ran without load until the exhaust temperature normalized in order to preserve engine stability. Data collection commenced after the stabilization of the issue, using the biodiesel blend fuel line under scrutiny. Each test was done three times to guarantee the precision and reliability of the results. Temperature thermocouples exhibited a significant range of 0–1300 K, with an error of ± 0.15 and an accuracy of ± 1 °C. The load was applied within the range of 250–5000 W, with an accuracy of ± 10 W, and an uncertainty of ± 0.2. The pressure was quantified between 0 and 250 bar using a pressure transducer with an uncertainty of ± 2 and an accuracy of ± 1. The global uncertainty of the experimental rig is assessed at 3.1%. The computation of the total experimental result uncertainty is shown in Eq. (1).

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \ldots\ldots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2} \quad (1)$$

W_R denotes the overall uncertainty of the test apparatus. The parameters x and R denote the dependent and independent variables, respectively. The line diagram showing the tested fuels and experimental measurements is shown in Fig. 3,

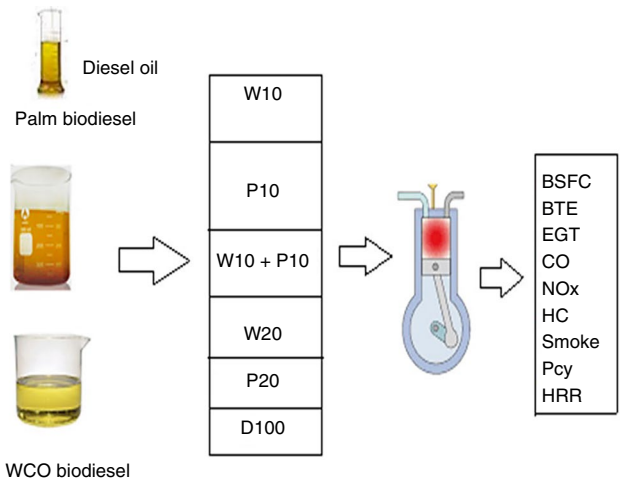


Fig. 3 Experimental line diagram

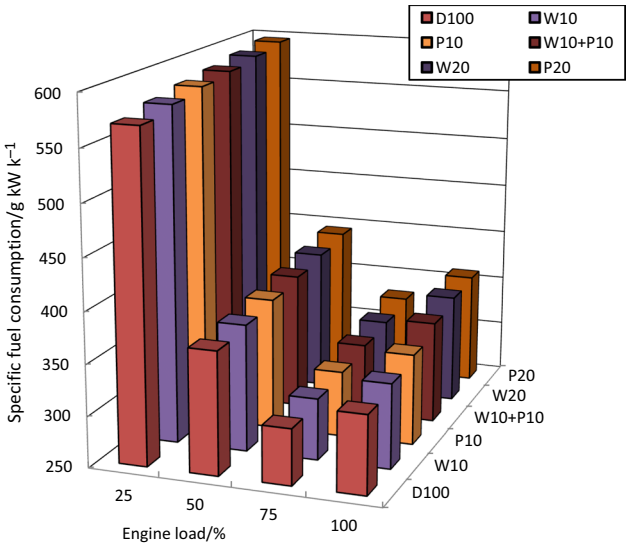


Fig. 4 Specific fuel consumption of methyl ester combinations at load change

Results and discussion

Brake-specific fuel consumption (BSFC)

The relationship between engine output power and specific fuel consumption for blends of diesel and methyl ester is shown in Fig. 4. At every load, the methyl ester's BSFC was greater than pure diesel. Because of the lower calorific value of methyl ester in diesel fuel, more fuel is required to generate the equivalent amount of load. Biodiesel exhibits increased specific fuel consumption as a result of its greater density, lower volatility, lower calorific value, worse combustion characteristics, and increased viscosity [24]. The volatility of biodiesel decreases, while its viscosity and density increase because of frictional forces that lead to problems in fuel atomization and heterogeneous mixing of fuel and air. This process subsequently results in partial ignition and elevated brake-specific fuel consumption (BSFC). The utilization of methyl ester and its combinations leads to an increase in fuel consumption, which offsets the reduction in brake output power, thereby preserving engine efficiency. The larger bulk modulus of biodiesel compared to diesel fuel results in a quicker combustion process and increased noise production during fuel injection system operation. The output power of biodiesel and its mixtures diminishes owing to increased fuel consumption. Pure biodiesel can harm engine parts and clog filters and nozzles because it grows denser and more viscous in colder climes. The blend W10 + P10 was demonstrated to have better and superior qualities in terms of density, calorific value, and viscosity with regard to palm, WCO biodiesel, W20, and P20. By combining hybrid

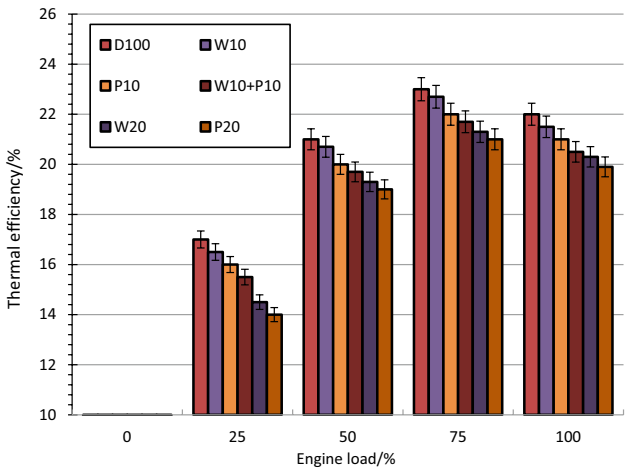


Fig. 5 Effect of biodiesel mixtures at load variation on BTE

biodiesel, it is possible to achieve simultaneous improvements in vaporization, cold properties, density, viscosity, and calorific value, The most significant gains in BSFC for P10, W10, W10 + P10, W20, and P20 were 1.5%, 3.5%, 6%, 7%, and 9%, respectively, about diesel fuel at 100% brake power. Results were validated by references [40, 41].

Brake thermal efficiency (BTE)

Figure 5 shows the variations in thermal efficiency between diesel mixtures and those containing methyl ester. Brake power and fuel consumption were both affected by the engine load. The BTE decreased due to the elevated methyl ester concentration of the test fuels. BTE rose to a maximum and fell as engine output power increased. Increases in heat loss and BSFC are shown at lower engine loads. Most significantly, under greater engine loads, the elevated temperature of the gas cylinder there encouraged improved fuel combustion efficiency. Fuel consumption and friction loss both rise as brake power increases. Reduced BTE was shown by the methyl ester's increased viscosity, worse combustion, and lower volatility. Problems with atomization, fuel–air homogeneity, and vaporization as well as fuels with lower calorific values may be the reason for this decline in BTE about diesel fuel. Pure biodiesel can harm engine parts and clog filters and nozzles because it grows denser and more viscous in colder climes. The blend W10 + P10 was demonstrated to have better and superior properties in terms of density, calorific value, and viscosity with regard to palm, WCO biodiesel, W20, and P20. Hybridization was used to blend the benefits of various biodiesels while minimizing their drawbacks. By combining hybrid biodiesel, it is possible to achieve simultaneous improvements in vaporization, cold properties, density, viscosity, and calorific value. At maximum load, the greatest BTE reductions for P10, W10, W10 + P10, W20, and P20 were 2, 4, 5.5, 6.5, and 10%, respectively, about crude diesel. The literature supported the conclusions [39, 40].

Exhaust gas temperature (EGT)

The relationship between output power and EGT for diesel and methyl ester mixes is shown in Fig. 6. As the brake power rose, the exhaust temperature for each test fuel steadily climbed. More fuel was used to support the greater loads, which raised the EGT. For every test fuel, the exhaust gas temperature rose in direct proportion to the rise in fuel consumption at higher loads. An additional potential might be increased exhaust gas temperatures resulting from the need to use more diesel fuel to maintain the increasing engine load. As a result, the exhaust would lose more heat. Diesel-methyl ester combinations produced EGT higher than pure diesel across the complete load range due to their lower BTE and worse combustion. For biodiesel mixtures, the heat loss in exhaust rises as thermal efficiency decreases. Methyl ester's lower BTE is explained by its higher density, less volatile, worse combustion, and higher viscosity in comparison with diesel. Compared to crude diesel, fuels with lower calorific values and higher viscosity as well as difficulties with atomization, fuel–air mixing, and vaporization might explain the decline in thermal efficiency and rise in BSFC [17, 24]. The blend W10 + P10 was demonstrated to have better and superior characteristics in terms of density, calorific value, and viscosity with regard to palm, WCO biodiesel, W20, and P20. By mixing hybrid biodiesel, it is possible to achieve simultaneous improvements in vaporization, cold properties, density, viscosity, and calorific value. At

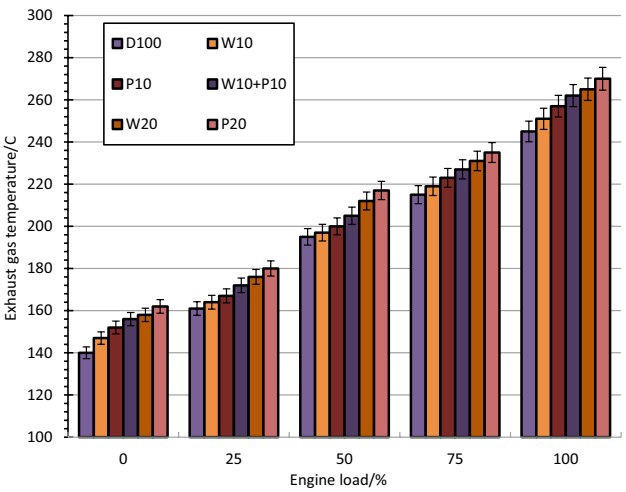


Fig. 6 Influence of methyl ester blends on EGT at load variation

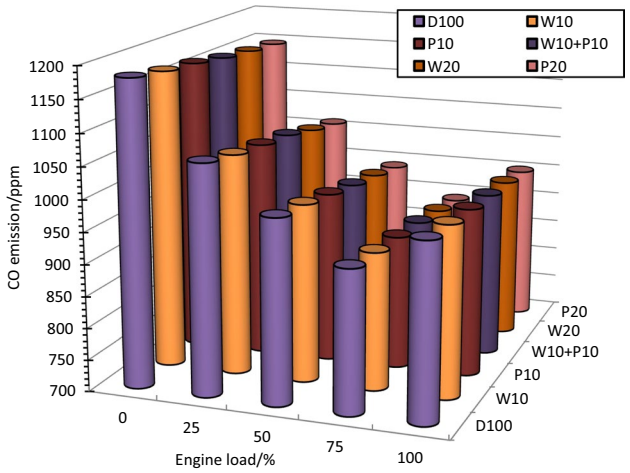


Fig. 7 Carbon monoxide emissions of methyl ester mixtures at engine output load changes

full brake power capacity, the largest gains in EGT for P10, W10, W10 + P10, W20, and P20 were determined to be 2.5, 4, 6, 7, and 8%. The results were agreed with the literature [34, 35].

CO emission

The impact of output brake power on carbon monoxide levels for blends of biodiesel and crude diesel is shown in Fig. 7. As output power grows, CO emissions decrease until a minimum is reached, beyond which they escalate. When the air–fuel ratio is high, carbon monoxide (CO) emissions happen because it becomes harder to acquire the oxygen needed for the fuel to completely oxidize the CO. Pure diesel releases more carbon dioxide into the atmosphere than methyl ester does. The oxygen ratio in biodiesel molecules encourages burning and changes the direction of the fuel-rich zone that builds and improves oxidation. The amount of oxygen in methyl ester is one element for CO_2 emissions to increase. An extended ignition delay period limits the fuel's ability to oxidize, either completely or partially. Diesel fuel was shown to have higher CO emissions or incomplete combustion emissions, as a result of this occurrence. Diesel fuel combusts for a reduced duration due to the extended ignition delay. The CO of methyl ester from the exhaust pipe before it could undergo full combustion due to insufficient time for secondary oxidation. The explanations provide a detailed account of why the diesel fuel exhibited higher carbon monoxide concentrations. Mixture W10 + P10 was used to have better and superior properties in terms of density, calorific value, and viscosity with regard to palm, WCO biodiesel, W20, and P20. Hybridization aimed to blend the benefits of various biodiesels while minimizing their drawbacks. By combining hybrid biodiesel, it is possible to achieve simultaneous improvements in vaporization, cold properties, density, viscosity, and calorific value. Blends P10, W10, W10 + P10, W20, and P20 exhibited the most significant reductions in CO emissions while using diesel fuel at peak load, with respective reductions of 0.6%, 1.2%, 2%, 2.2%, and 3%. The findings were consistent with prior research [35, 40].

NOx emission

The effect of various fuels on nitrogen oxide concentrations as engine brake power fluctuates is seen in Fig. 8. The cylinder temperature, oxygen percentage, residence time, and ignition delay are the main variables that affect NOx emissions. The temperature of the cylinder increases as engine load rises. Increased fuel usage in premixed combustion and elevated cylinder gas temperatures both contribute to higher NOx emissions. The primary factors contributing to the increase in NOx emissions include elevated levels associated with increased engine loads and heightened fuel consumption linked to greater engine brake power. The increases in cylinder and adiabatic flame temperatures result in a higher quantity of nitrogen oxide emissions released. Internal cylinder turbulence intensified with rising engine output power, leading to a more concentrated mixture of fuel and air. Thermal NOx is created when oxygen and dissociated nitrogen interact at high combustion cylinder temperatures. Nitrogen oxide concentration increases resulted from the rise in biodiesel percentage. The interaction between airborne oxygen and the cylinder combustion temperature resulted in the thermal NOx formation. Mixtures of methyl ester contained larger values of nitrogen oxides than diesel fuel

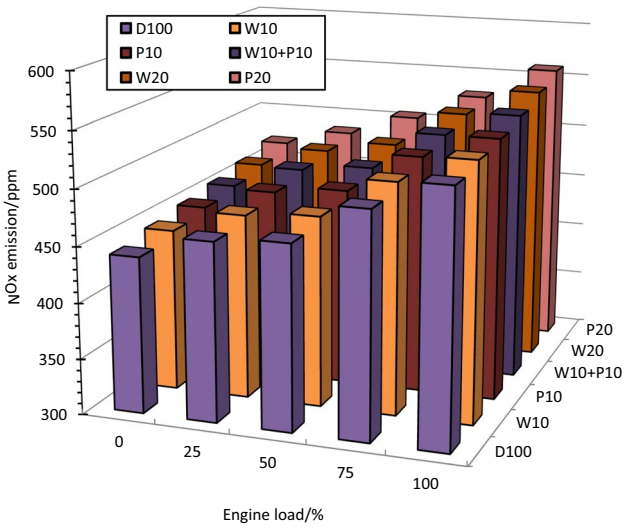


Fig. 8 NOx content in methyl ester blends at different engine brake power

because of elevated cylinder temperatures, increased oxygen content, and higher adiabatic flame temperatures. Pure biodiesel can harm engine parts because it grows denser and more viscous in colder climates. The mixture W10 + P10 was demonstrated to have better and superior characteristics in terms of density, calorific value, cetane number, viscosity, and palm, WCO biodiesel, W20, and P20. Hybridization was used to blend the benefits of various biodiesels while minimizing their drawbacks. By combining hybrid biodiesel, it is possible to achieve simultaneous improvements in vaporization, cold properties, density, viscosity, and calorific value. Concerning pure diesel at 100% engine load, the biodiesel blends P10, W10, W10 + P10, W20, and P20 exhibited the largest increases in NOx concentration of 1%, 2%, 3%, 4%, and 6%, respectively. The findings were adapted with the references [27].

HC emission

Differences in unburned hydrocarbon levels between biodiesel and pure diesel mixtures in relation to engine output power are depicted in Fig. 9. As engine load increased and engine component brake power decreased, HC emissions rose for all blends. This is attributable to the richness of the fuel–air combination and the oxygen deficiency caused by high engine brake power operation. Because of its high oxygen content, methyl ester's hydrocarbon concentrations decrease at higher load ranges. Because methyl ester contains more oxygen than ordinary diesel oil, it may oxidize more easily, which lowers the amount of hydrocarbon values [10, 17]. Hydrocarbon emissions diminish when crude diesel is replaced with biodiesel, which has a lower ignition delay and superior cetane number. Blends of biodiesel with diesel fuel exhibited enhanced ignition and combustion properties. When diesel oil is substituted with biodiesel, the oxidation is improved and leads to HC reduction. Biodiesel can cause problems in engine parts because it grows denser and more viscous in colder regions. Blend W10 + P10 was demonstrated to have better and superior properties in terms of density, calorific value, viscosity, cetane number in comparison with palm, WCO biodiesel, W20, and P20. By mixing hybrid biodiesel, it is possible to achieve simultaneous improvements in vaporization, cold properties, density, viscosity, and calorific value. Under full-load conditions, the biodiesel blends exhibited the most significant reductions in hydrocarbon emissions, namely 5%, 6%, 9%, 11%, and 15% for P10, W10, W10 + P10, W20, and P20, respectively. The results were consistent with the literature [21].

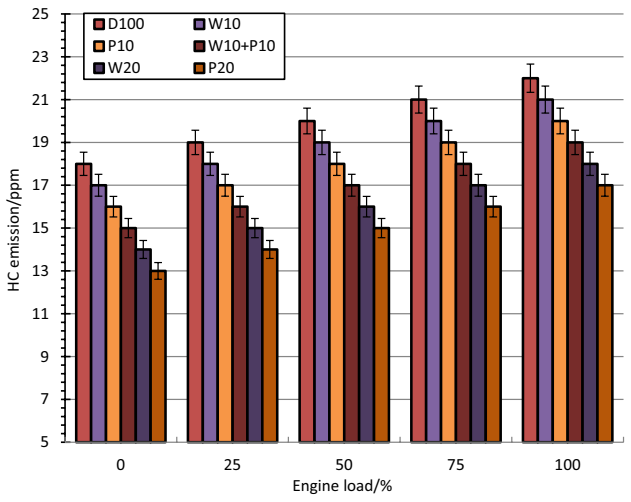


Fig. 9 Influence of methyl ester combinations on HC concentration at engine output range

Smoke emission

The impact of palm and waste cooking methyl ester combinations on smoke at load variation is displayed in Fig. 10. Smoke concentrations increased due to the rise in consumed fuel that was proportionate to engine load. At lower engine load, less smoke production occurs owing to the increased oxygen ratio. Smoke is evident due to heightened fuel consumption and oxygen deficiency with elevated engine braking power. The intrinsic oxygen in methyl ester resulted in a reduction in smoke concentrations as the methyl ester proportion increased leading to improved oxidation. The factors contributing to the increase in smoke opacity include heightened fuel consumption and output power. Increased oxygen concentration of the methyl ester results in a slower combustion rate and generates particles that undergo more complete oxidation, improved ignition, and boosted combustion, hence reducing smoke emissions [8, 21]. Biodiesel blends produced less smoke than conventional diesel. The increased oxygen content of methyl ester augmented combustion

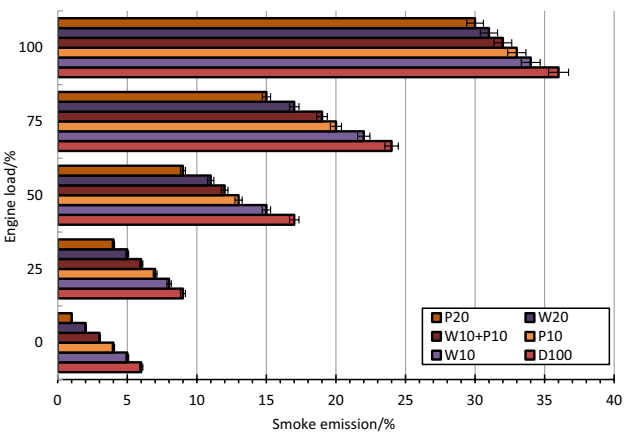


Fig. 10 Emission of smoke from biodiesel blends at varying loads

efficiency, reduced smoke emissions, and improved ignition. The blend W10 + P10 was demonstrated to have better and superior qualities in terms of density, calorific value, and viscosity with regard to palm, WCO biodiesel, W20, and P20. Using a hybrid biodiesel mixture can improve vaporization, cold properties, density, viscosity, and calorific value. Significant declines in smoke values at peak output power were 5, 7, 9, 10, and 12%, respectively. Findings were corroborated by previous work [37] at peak load of 5, 7, 9, 10, and 12%. The findings were supported by the prior research [40, 41].

In-cylinder pressure (P_{cy})

Figure 11 shows the full-load cylinder pressure for methyl ester mixtures. Each fuel that was tested had a constant orientation of cylinder pressure. Diesel oil has a higher peak Pcy than blends of biodiesel. It diminishes with an increasing amount of biodiesel because of its shorter ignition delay and elevated cetane number in relation to regular diesel. The cylinder had a greater volume of biodiesel prior to ignition due to lower ignition delay. The fuel ignites abruptly upon attaining the requisite temperature and pressure. The diesel test fuel's prolonged ignition delay and greater fuel buildup allowed it to reach its highest peak cylinder pressure. Decreased calorific value and insufficient atomization and vaporization of methyl ester combinations lower the cylinder pressure. Because it ignited more rapidly, biodiesel burned overall more quickly than diesel fuel. More consumed methyl ester in diesel oil is shown in the diffusion phase about the premixed phase. The atomization and vaporization problems are made worse by the heavier and more viscous nature of methyl ester and its mixtures compared to diesel fuel, which significantly alters the spray properties. Consequently, it is plausible that the two fuels will collaborate to prolong the physical delay period, leading to diminished maximum P_{cy} and worse combustion. Diesel fuel combusts more rapidly, and the fuel injection activates sooner when the bulk modulus of the methyl ester is elevated. Biodiesel fuel's oxygen concentration accelerates fuel droplet evaporation and reduces ignition delay. The consumed fuel is increased in the diffusion stage about premixed which declines the cylinder pressure. Mixing of W10 with P10 showed better and superior characteristics in terms of density, calorific value, and viscosity with regard to palm, WCO biodiesel, W20, and P20. The goal of hybridization was to blend the benefits of various biodiesels while minimizing their drawbacks. By combining hybrid biodiesel, it is possible to achieve enhancements in vaporization, cold properties, density, viscosity, and calorific value. Concerning pure diesel at maximum output power, the most significant peak reduction Pcy was seen to be 1, 1.8, 2.8, 3.5, and 4% for P10, W10, W10 + P10, W20, and P20, respectively. The findings were corroborated by references [10, 21].

Net heat release rate (HRR)

HRR for methyl ester mixtures utilizing pure diesel at rated speeds and highest load is described in Fig. 12. The seen patterns showed similarities between blends of diesel and biodiesel. The mixed methyl ester's maximum heat release rates were lower than pure diesel when the methyl ester ratio was increased. In comparison with methyl ester, diesel fuel exhibits lower cetane number and longer ignition delay. A reduced peak HRR was achieved since biodiesel blends utilized less fuel than diesel during the premixed phase. The diminished calorific values of methyl ester produced a reduced heat release rate. As the concentration of methyl ester increased, HRR and P_{cy} values in these fuels

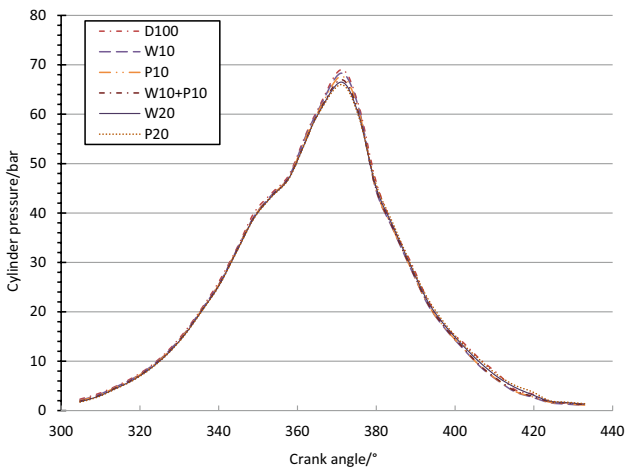


Fig. 11 Impact of biodiesels on cylinder pressure at high load

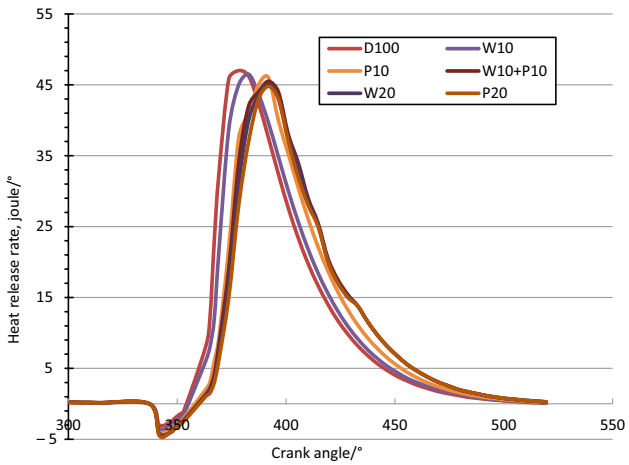


Fig. 12 Effect of blended diesel–biodiesel on HRR at full engine brake power

consistently diminished. Diesel fuel's greater density and viscosity necessitate that its injection precedes that of the other blend. In relation to diesel oil, methyl ester necessitates a greater quantity of fuel in premixed phase and a reduced quantity during the diffusion phase. The brief premixed time in biodiesel blends results in premature combustion. Biodiesel blends with a high cetane number accelerate the premixed phase and advance the combustion phase earlier in the compression stroke. The rapid ignition of the methyl ester resulted in complications with evaporation, atomization of fuel, and inadequate mixing of fuel–air mixture. Compared to diesel oil, biodiesel fuel consumes less fuel during the initial diffusion phase but more fuel during the subsequent premixed phase. Early burning is induced by the short-premixed combustion phase seen in biodiesel blends. In comparison with methyl ester blends, the blend W10 + P10 was shown to have higher and superior attributes in terms of density, calorific value, and viscosity. Hybridization aimed to minimize the disadvantages of different biodiesels while combining their advantages. In a comparison of pure biodiesel and diesel oil at full engine load, the most significant reductions in peak HRR were observed at 1, 2, 3.2, 4, and 4.5% for W10, P10, W10 + P10, W20, and P20, respectively. The references [24] agreed on these results.

Comparative analysis

Performance, emissions, and combustion parameters of diesel engines using P10, W10, P10 + W10, P20, and W20 are contrasted to diesel oil in Table 2.

Table 2 Relative changes in emissions, combustion, and performance parameters of methyl ester blends at peak load ((−) denotes a decrease, while (+) denotes an increase)

Relative change/%	P10	W10	P10 + W10	P20	W20
BSFC	+1.5%	+3.5%	+6%	+7%	+9%
BTE	−2%	−4%	−5.5%	−6.5%	−10%
EGT	+2.5%	+4%	+6%	+7%	+8%
CO	−0.6%	−1.2%	−2%	−2.2%	−3%
HC	−5%	−6%	−9%	−11%	−15%
NO_x	+1%	+2%	+3%	+4%	+6%
Smoke	−5%	−7%	−9%	−10%	−12%
Peak P_{cy}	−1%	−1.8%	−2.8%	−3.5%	−4%
Peak HRR	−1%	−2%	−3.2%	−4%	−4.5%

Conclusions

The present investigation utilized waste cooking and palm biodiesels, together with their blends, to assess emissions, combustion properties, and diesel engine performance. WCO and palm oil were utilized to efficiently produce methyl ester, which was then blended with crude diesel at percentages of 10% and 20% volumetrically. In compliance with ASTM guidelines, the properties of pure biodiesel and diesel oil were discussed. The principal conclusions of the study are encapsulated as follows:

- Through esterification and transesterification, palm biodiesel and WCO biodiesel were successfully produced. These biodiesels exhibited differences in density, viscosity, cetane number, and lower heating value about fossil diesel.
- The increase in the biodiesel ratio led to a higher BSFC and a decline in thermal efficiency. For instance, specific fuel consumption increased by 1.5, 3.5, 6, 7, and 9% for P10, W10, W10 + P10, W20, and P20 blends, respectively, while thermal efficiency decreased by 2 to 10% at full engine load. Additionally, EGT was increased by 2.5% to 8% across these blends.
- The mixtures showed significant reductions in CO concentrations, with reductions ranging from 0.6 to 3%. However, an increase in NOx emissions was shown, varying between 1 and 6%. Smoke concentration reductions of up to 12% and hydrocarbon emission reductions of up to 15% were noted.
- The largest decreases in peak cylinder pressure for P10, W10, W10 + P10, W20, and P20 were 1, 1.8, 2.8, 3.5, and 4%, respectively, compared to pure diesel at maximum brake power, but the biggest drops in peak HRR were 1, 2, 3.2, 4, and 4.5%, respectively, at 100% output power.
- The research indeed highlighted the benefits of biodiesel blends, particularly hybridizing palm and waste biodiesels. Hybridizing two biodiesels derived from different feedstocks, namely palm and waste cooking oils, enhances the attributes of P20, W20, palm, and WCO biodiesel, including density, cetane number, calorific value, viscosity, and flash point. The changes in physical and chemical properties result in increased heat release rate and cylinder pressure, decreased emissions of CO, HC, and smoke, and enhanced thermal efficiency.

The research indeed highlighted the benefits of biodiesel mixtures, particularly hybridizing palm and waste cooking oils. The higher fuel consumption rate for biodiesel blends compared to conventional diesel was primarily due to their lower energy density, which required more fuel to achieve

the same power output. Crude biodiesel produced from palm and WCO may have issues with vaporization and atomization because of its higher density and viscosity. Because pure biodiesel becomes denser and more viscous in colder climates, it can damage engine components and clog filters and nozzles. Additionally, the increased NOx emissions were linked to the higher oxygen content in biodiesel, which led to higher combustion temperatures. In order to enhance fuel properties, lower emissions, and boost engine performance, hybrid biodiesel is created by mixing two or more biodiesel blends. Hybridization aims to minimize the disadvantages of different biodiesels while combining their advantages. Hybrid biodiesel should have the lowest density, the lowest viscosity, and the highest calorific values. Because of the lower oxygen content and cylinder temperature, hybrid biodiesel W10 + P10 exhibited lower NOx emissions compared to W20 and P20. When compared to W20 and P20, the biodiesel blend W10 + P10 showed better properties, such as decreased viscosity, decreased density, decreased cetane number, and enhanced calorific value. Regarding P10 and W10, there is a considerable in BSFC for W10 + P10. The decrease of fuel consumption can be decreased by using biodiesel mixtures with properties near diesel oil. The blending of biodiesels from different feedstocks reduces carbon emissions. By raising the demand and pricing of agricultural goods, biodiesels are predicted to boost the economy, decrease greenhouse gas emissions, and decrease reliance on imported petroleum and the political and economic fragility that goes along with it. Hybrid biodiesels from palm and WCO are less costly because the percentages of biodiesel are lower and near diesel oil.

Life cycle, sustainability, environmental, and cost analysis of biodiesel application

There are environmental advantages to producing biodiesel from plant oils that absorb carbon dioxide during growth. Using biodiesel releases this stored carbon, maintaining the carbon cycle's equilibrium. In contrast, fossil fuels release more carbon dioxide, which raises greenhouse gas (GHG) emissions. Because biodiesel reduces greenhouse gas emissions overall, it is therefore a more environmentally friendly choice than fossil fuels. The selection of feedstock determines sustainability in the production of biodiesel. When burning, biofuels leave a lower carbon footprint than fossil fuels. However, the production of biofuel crops still needs a lot of water and oil resources. Using biodiesel lowers life cycle emissions. Food production should not be hampered by the feedstocks used to create sustainable biodiesel. Sustainable biodiesel should prioritize biodiversity and critical areas while avoiding deforestation. By converting waste cooking oil, animal fats, and agricultural waste into sustainable biodiesel, competition with food production is reduced and the fuel's overall sustainability profile is improved. The sustainability of the biodiesel production process may stimulate the use of local feedstock, such as palm oil or food waste.

Available feedstocks from waste, non-food, and edible sources are needed to produce biodiesel. Edible and virgin oils need water, fertilizer, and land area. The high cost of producing biofuel rises as a result. The cost of processing oil and turning it into methyl ester is higher. Waste cooking oil and animal fat are examples of sustainable waste feedstock that can be used to ensure the economic viability of biodiesel mixtures. Although using hybrid biodiesels improves emissions and engine performance, it is vital to take into account the associated increase in fuel prices. Engine performance gains and pollution reductions should be balanced with the expense of biodiesel. The anticipated cost of producing biodiesel using base-catalyzed transesterification of used cooking oil is US$1.2/L. Because waste cooking oil only costs about half as much as biodiesel, it was a financially feasible fuel. Consequently, biodiesel costs more than twice as much as diesel fuel on average.

Limitations of the study

Furthermore, the higher oxygen concentration in biodiesel, which raised the combustion temperature, was connected to the higher NOx emissions. In comparison with biodiesel blends, hybrid biodiesel W10 + P10 showed lower NOx emissions due to its lower oxygen content and cylinder temperature. Recirculation of exhaust gas plays an important role in improving the combustion in the engine and reducing NOx emissions. It recirculates a portion of an engine's exhaust gas back to the engine cylinders. This process lowers the combustion temperature, significantly reducing the formation of nitrogen oxides [42]. Exhaust gas recirculation (EGR) is used from 10 to 30%. By employing Selective Catalytic Reduction (SCR) technology, NOx can be reduced. Aqueous urea solution is used in SCR a system that is transformed into ammonia when it is introduced into a catalytic converter [43]. Even though the application of hybrid biodiesels enhanced engine performance and emissions, it is important to carefully consider the corresponding rise in fuel costs. To guarantee the economic feasibility of these biodiesel blends, biodiesel can be produced from available waste feedstocks. A balance between the biodiesel cost and engine performance improvements and emissions decreases should be considered.

Future research perspectives

To build upon these findings, future research could focus on optimizing the blending ratios of various biodiesel feedstocks to achieve an ideal balance between engine performance, combustion, and emissions. Further investigation into advanced combustion techniques, such as variable compression ratios and dual-fuel operation, could enhance the performance of biodiesel blends. Additionally, exploring the long-term effects of using these biodiesel blends on engine wear and durability will provide more insights into their practical application. Finally, life cycle analysis (LCA) of methyl ester making from different feedstocks could offer a comprehensive assessment of their environmental impact, guiding the development of more sustainable biofuels.

Acknowledgements The authors extend their appreciation to Prince Sattam bin Abdulaziz University for funding this research work through the project number (PSAU/2023/01/27425).

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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