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Investigation of waste cooking and castor biodiesel blends effects on diesel engine performance, emissions, and combustion characteristics

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ABSTRACT

Waste cooking (WCO) and castor oils are used as methyl ester feedstocks. By esterification and transesterification of castor and WCO, biodiesels were created and combined with diesel in proportions of 10 % and 20 %. Diesel engine emissions, performance, and combustion were computed at 3000 rpm rated speed and load variation. Highest increases in specific fuel consumption of 2, 3.5, 5.5, 6, and 8.5 % were seen in the cases of waste cooking (10 %), castor biodiesel (10 %), blending (10 %), waste cooking (20 %), and castor (20 %) when diesel fuel was utilized at full load. Thermal efficiencies were decreased by 2.5, 4, 5, 6, and 9.5 % in proportion. Compared to diesel oil, WB10, CB10, WB10+CB10, WB20, and CB20 displayed the biggest reductions in CO emissions of 0.5, 1.5, 2.5, 3, and 3.5 %, respectively; in contrast, NOx concentrations climbed to 1.5, 2.5, 3.5, 5, and 6.5 %, respectively. Largest reductions in hydrocarbon emissions were shown for biodiesel blends as 6, 7, 10, 12, and 14 %, respectively. Largest declines in smoke at peak load were seen for WB10, CB10, WB10+CB10, WB20, and CB20, with respectively values of 6, 8, 10.5, and 11 %. Decrements in maximum cylinder pressure were 1.5, 2, 2.3, 3.5, and 4.5 % at peak load related to diesel. There were 1.5, 2.5, 3, 4.5, and 5 % drops in peak HRR, respectively. Improvement of emissions, performance, and combustion characteristics associated with diesel engine fueled by mixtures of WCO, and castor methyl ester is achieved through the hybridization of feedstocks with different properties as 10 % castor and 10 % WCO biodiesels.

1. Introduction

Concept of using biodiesel fuels as a sustainable alternative for conventional petroleum diesel has garnered a lot of attention in recent studies [1]. Many scholars are looking into the many aspects of producing and using biodiesel as the pressing demand for clean and renewable energy sources increases [2,3]. Methyl ester is produced from different sources, such as used cooking oil, animal fats

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like lard, and eatable and non-eatable oils [4,5]. Waste cooking oil (WCOB) biodiesel exhibits reduced concentrations of carbon monoxide (CO) and hydrocarbon (HC) due to its higher content of oxygen, lower aromatic content, and lower sulfur concentration when it is compared to conventional diesel fuel [6–8]. We looked at the performance and emissions of a diesel engine which is based on direct-injection, running on waste cooking biodiesel (WCOB) mixed with ferric chloride and aluminum. Their results show that using WCOB significantly lowers emissions [9,10]. There were 54.17 %, 50 %, and 22.69 % reductions in smoke, CO, and HC concentrations, respectively. The growth in NOx reached to 18.32 %. The researchers examined the performance of a single-cylinder CI engine concerning mixtures of nanoparticles with B10 and B5 from blends of used cooking waste. For every fuel combination, they employed 30, 60, and 90 ppm nanoparticles [11].

Nanoparticles introduced into biodiesel blends achieved significant increases in EGT (5.57 %), BTE (8.12 %) and output power (3.67 %) at all engine speeds. Castor oil plants exhibit rapid growth and are commonly observed as small perennial shrubs covered with branches or as softwood trees. Moreover, castor plants have the potential to thrive in marginal zones that are not favorable to the cultivation of food crops due to their ability to survive adverse climatic condition such as drought. Castor seeds are an important resource for the processing and production of biodiesel because they possess a greater capability for producing oil than other non-eatable oil seeds [12]. Castor seeds frequently possess an oil concentration of 40–55 % (w/w), substantially higher potential than soybeans (15–20 %), sunflowers (25–35 %), rapeseeds (38–46 %), and palms (30–60 %) [13]. Properties of pure castor oil biodiesel 10% and diesel mixture (B10) were examined. The B10 blend met all criteria, while pure distillation temperature and kinematic viscosity of COME adapted with ASTM D6751 biodiesel specifications [14,15]. Because of its exceptional engine lubricating properties, castor oil methyl ester (COME) has shown to be a viable substitute for diesel. The study examined the performance parameters of single-cylinder diesel engine running on 4-stroke cycle, using three diesel-biodiesel combinations (B05, B10, and B20), in comparison to standard diesel fuel [16–19]. Blended fuels were shown to function similarly to diesel at 1500 rpm. The engine speed variation was used to compute the performance parameters ranged from 1000 to 2400 rpm [20]. The research findings indicate that increasing the proportion of castor oil methyl ester in the mixture produced a slight reduction in brake power while concurrently causing an increase in fuel consumption. However, when castor oil biodiesel was added to the mixture, NOx emissions were increased, but CO_2 and carbon monoxide emissions were dropped. B25 was considered the recommended alternative to diesel engines [21].

When it came to the brake thermal efficiency at maximum load, B10 outperformed the other two mixtures. When compared to standard diesel fuel, the blends' increased COME % led to reductions in CO, NOx, and HC emissions. The results of a comparison study between diesel and biodiesel blends showed that the biodiesel blend had greater net heat release rates and higher peak pressures. The results demonstrated that 20 % addition of castor biodiesel to diesel could be made without altering the fuel injection mechanism. Blends of B0, B5, and B10 were used in water-cooled, four-stroke diesel engine running under 80 % continuous load with and without 2 % DME (dimethyl ether) were studied [23]. The results demonstrated that nitrogen oxide (NOx) emissions might be reduced by adding more castor biodiesel blends and reducing the HRR. As the ratio of castor methyl ester in the fuel mixture increased, the levels of nitrogen oxide (NOx) emissions also were increased [24]. The research investigated key performance characteristics during the engine speed variation from 1000 to 2400 rpm. Findings demonstrated a direct correlation between the quantity of castor biodiesel in the mixture and the quantity of biodiesel used for the brake power consumption. An inverse correlation was seen for brake power output and fuel consumption. Conversely, the addition of castor oil biofuel achieved the increase in NOx concentrations while simultaneously reducing carbon dioxide and carbon monoxide emissions. According to their findings, the best mixture for diesel engines is B25, which includes 25 % biodiesel. The research investigation focused on the study of diesel and castor oil blends comprising 15 %, 10 %, and 5 % methyl ester [25,26].

At full load, B10 mixture exhibited improved BTE compared with other fuels. The incorporation of biodiesel into diesel oil resulted in minimizing the amounts of CO and HC. Further study was conducted to investigate the combustion characteristics, with a particular focus on the effects of crank angle and ignition delay on cylinder pressure and heat release rates. Similar studies show that fuels with mixtures of diesel and biodiesel have higher peak cylinder pressures and rates of heat release. Numerous studies have shown that B20 improves thermal efficiency when compared to diesel fuel alone. It was noticed that B20 increased engine performance because of its flash point, density, calorific value and viscosity are near to diesel [27]. Nevertheless, adding biodiesel to diesel in engines has several limitations. Some disadvantages include higher density, increased viscosity, insufficient fuel atomization, reduced pour points and cloud, sticking of piston ring, elevated NOx emissions, and problems in cold start [28,29].

Researchers studying fuels and engines must investigate sustainable fuels for internal combustion engines due to climate change and strict pollution rules in many nations. A few significant recent studies are also examined to determine the technology's shortcomings, possibilities for development, and future research directions. Even though scientists have been able to solve some problems, additional research is still required to lessen risks and improve the fuel's efficiency and environmental friendliness when used as a fuel for diesel engines [30]. Tyre oil mixtures (10 % and 20 %) were compared with diesel fuel. Compared to diesel, NOx emissions were lowered by around 30 % with both mixtures. There was 35–60 % decrease in PM emissions and 5–20 % decrease in PN emissions. Carbon monoxide (CO) rose by 10 % relative to the reference diesel. Tyre oil may be used as an alternative to conventional diesel fuel, depending on the engine's performance and emission results [31]. In a fluidized bed reactor, the carbonaceous solid wastes in the forms of bagasse, jute stick, and rice straw were pyrolyzed. Physical characteristics, calorific value, elemental (CHNOS) analysis, and chemical composition using Fourier Transform Infrared (FTIR) spectroscopy were the fuel properties that were compared. The outcomes demonstrated that biomass pyrolysis might be a viable source of liquid hydrocarbon fuel [32]. When cold starting, plain diesel generates more blow-by than oxygenated fuels. Diesel is not as efficient between hot and cold starts as oxygenated fuels. The reason why oxygenated fuels perform better during cold starts might be because to their blow-by hindered qualities, which include increased lubricity and viscosity [33]. The neat jatropha methyl ester's fuel characteristics, such as its density, kinematic viscosity, cetane number, and flash point, were found to be almost identical to those of neat diesel fuel. Virtually every property falls inside the ASTM standard definition [34]. The experimental findings demonstrated that, for all surrogate blends, decreased NOx emissions were associated with a penalty in particle mass, particulate number, and CO emissions without a discernible decline in engine performance [35]. Particulate oxidative potential is significantly influenced by the oxygen concentration of fuel molecules. Lower emissions are a direct result of higher oxygen content in the biodiesels under consideration. The oxygen content reduces emissions that are important in terms of health impacts [36].

One of main objectives of this research is to provide a fuel that can be used as alternative incorporates biodiesel blends derived from WCO and castor methyl esters as an additional agent to investigate the impact on CI engines' operation, combustion, and emissions characteristics. Disposal of waste cooking oil causes harm effects on human health and environment. WCO should be converted to useful energy which is benefit from economical and environmental considerations. The literature does not address mixing several kinds of biodiesel derived from diverse feedstocks. Crude biodiesel generated from castor and WCO has higher value of density, viscosity and lower calorific values, which might cause vaporization and atomization issues. Application of biodiesel is reliable and helpful for ecological sustainability view. Thus, its pure application in diesel engines may be restricted by using pure biodiesel in cold climate. Both combustion and performance of engine are affected by the different chemical and physical properties of pure biodiesel in comparison to conventional diesel. Because of higher density and viscosity at low temperatures, pure biodiesel can cause damage to engine components and clog filters and nozzles. Combining different types of biodiesels might increase their benefits while decreasing their drawbacks. Blending of different feedstocks can provide biodiesel with greater advantages and fewer drawbacks. This implies that combustion, performance and diesel engines emission are enhanced when these hybrid biodiesel blends are used as fuel. To enhance combustion, emissions, and the performance of engine, this research is aimed at enhancing physical and chemical properties of biodiesels by their combination with other feedstock, such as castor oil and WCO. Performance analysis is shown at a constant speed and with varying loads. Biodiesels were created from castor and waste cooking oil and mixed with diesel at volume ratios of 10 % and 20 %. BTE, BSFC, EGT, HC, CO, smoke opacity and NOx are the most commonly used indicators in evaluation. In-cylinder pressure and net heat release rate are also calculated. Our study fills a knowledge gap in the usage of methyl ester blends produced from WCO and castor biodiesels with different properties by enhancing emissions, combustion, and engine performance.

2. Methodology

2.1. Tested fuel preparation

Pretreatment involves heating castor fatty acid distillate to 90 °C for 15 min to remove moisture, centrifuging and filtering away contaminants and gums, and neutralizing the pH of the water to prepare castor oil for use in methyl ester production. Following the pretreatment esterification procedure, castor fatty acid distillate is mixed with ethanol and H_2SO_4. Castor fatty acid distillate was heated to as high as 80 °C to remove moisture. The reactant mixture consists of 1 L of castor oil, 250 ml of ethanol, and 5 ml of H_2SO_4 for 3 hrs. Next, the free fatty acid (FFA) was measured. Once the FFA content is less than 2 %, the transesterification process is a base-catalyzed reaction that yields glycerin and mono-alkyl esters [37,38]. Ten grams of NaOH and 250 ml of ethanol were combined with the esterified oil. Adjust the oil temperature to between 65 and 70 °C. The oil and ethanol mixture were mixed, and the catalyst was agitated for 30 min. The combination has a maximum FFA concentration of 0.5 %. The mixture was forcefully mixed at 300 rpm for 90 min. In order to settle the mixture for 12 hrs, it was then placed in separate in a separate funnel. After the bottom layer, including glycerol and other contaminates, was eliminated, the top layer generated castor ethyl ester-containing alcohol and water. Three or four washings were required to get the glycerin out of the biodiesel and bring the water's pH down to neutral. After that, it was thoroughly mixed to remove the glycerol and any further contaminants. The moisture content was lowered using a rotary evaporator to obtain pure castor ethyl ester [39–41]. WCO was purchased from hotels, restaurants, and manufacturers. WCO was preheated and filtered to eliminate the moisture and contaminants. Maximum amount of FFA in the combination is 0.5 %. Catalyst of 1 % NaOH and 6:1 M ratio of ethanol were used. The catalyst and ethanol mixture was agitated for 30 min. Adjust the oil temperature to 65–70 °C. The mixture was aggressively agitated at 300 revolutions per minute for 1.5 hr. Following that, the mixture was placed in a separate funnel and left to settle down for 12 hrs. After removing the bottom layer, which included glycerol and other residuals, the top layer yielded methyl ester-containing alcohol and water. Biodiesel was washed with water many times. The moisture level was reduced to produce pure castor ethyl ester [40,41].

WCO and castor biodiesel mixtures were prepared in different volume ratios as 10 and 20 % as WB10, CB10, WB20 and CB20, respectively. The blending was continuously kept using magnetic stirrer with continuous agitation at 600 rpm for 30 min to produce uniform homogenization. The density and viscosity of biodiesel blends up to 20 % volume percentage are near to diesel oil. There are small deviations between biodiesel and diesel oil in viscosity and density. The mixing between methyl ester and crude diesel can be achieved without separation. Crude biodiesel produced from castor and WCO may have issues with vaporization and atomization because to its higher density and viscosity. Because pure biodiesel becomes more dense and viscous in cold climates, it can damage engine components and clog filters and nozzles. In order to enhance engine performance, lower emissions, and improve fuel properties, two or more biodiesel blends are combined to create hybrid biodiesel. Hybridization was done to reduce the disadvantages of different biodiesels and combine their advantages. Simultaneous improvements in vaporization, cold characteristics, density, viscosity, and cetane number can be obtained using a hybrid biodiesel combination. The biodiesel combination was prepared and tested to make sure it adhered to the established guidelines. It is necessary to have the highest calorific values, lowest possible density, and viscosity. Diesel oil properties should be close to hybrid biodiesel properties. In comparison to CB20 and WB20, the biodiesel combination CB10+WB10 demonstrated superior attributes such as decreased kinematic viscosity, decreased density, decreased cetane number, and increased calorific value. The required fuel characteristics and diesel engine's operating capabilities are achieved using hybrid biodiesel. Properties of tested fuels were shown in Table 1.

Table 1
Characteristics of castor and waste cooking biodiesel.

Properties	Method	Diesel oil	WB100	CB100	WB20	CB20	WB10+CB10
Density at 15.56 (°C), kg/m^3	ASTM D-4052	827	873	890	840	855	835
Calorific Value, kJ/kg	ASTM D-224	42100	39200	38400	41800	40700	42000
Kinematic Viscosity at 40 (°C), cSt	ASTM D-445	2.4	4.2	6.5	3	3.4	2.8
Cetane number	ASTM D-13	44	51	53	47	49	46
Flash Point, (°C)	ASTM D-93	72	150	170	92	110	81

2.2. *Experimental test rig*

The tests are conducted with on CI engine as the test engine. At 3000 rpm, the engine can produce a maximum torque of 26 N.m. The test engine specifications were described in Table 2. Cylinder pressure was monitored up to 250 bar using a water-cooled Kistler piezoelectric pressure transducer (model 601A) with sensitivity of 16.5 pc/bar and accuracy of 1.118 %. The piezoelectric pressure transducer was flush fitted to the cylinder head in order to eliminate pressure signal delay and prevent resonance in the pipe connection channel. The pressure sensor was attached to the charge amplifier (2692-A-0S4). The engine's output shaft had a proximity switch (Type LM12-3004NA) that was used to measure the piston's position. The pressure crank angle graphs were taken and analyzed to assess the combustion characteristics. High-speed data collection and processing were done using LABVIEW software and National Instruments data card (NI-USB-6210). A minimum of 125 cycles are gathered in order to improve the findings' accuracy and dependability. As the load is raised, the test fuels' cylinder pressure curve changes exhibit a diminishing tendency. A smoke opacity meter of OM-100 type is used to monitor the smoke. The device functions on a scale ranging from 0 to 100 %, with a resolution of 0.1 %. A KOEN KEG-500 portable exhaust gas analyzer is utilized for testing exhaust concentrations. Levels of carbon monoxide (CO) (0–10 %), hydrocarbons (HC) (0–9999 ppm), and nitrogen oxides (NOx) (0–5000 ppm, precision 1 ppm) were observed. Fig. 1 shows the test rig's schematic design. EGT is measured with 1 °C precision using K-type thermocouples. A burette made of glass having a range of 0–100 ml was used to quantify the consumed fuel volume at 1-min intervals. It has a precise reading range of 1 ml. A digital tachometer is utilized for evaluating the engine's rotational speed during testing. Performance characteristics such as BSFC, BTE, and EGT were measured. Monitoring was conducted on the emissions of HC, NOx, CO, and smoke exhaust.

Emissions of CO, NO_x and HC were converted from volume percentage, ppm and ppm to g/kWhr, respectively as shown in the following equations.

$$\text{CO (g/kWhr)} = 0.003591\text{x CO (ppm)}$$

Table 2
Engine specifications.

Parameters	Specifications
Engine model	Lombardini Group's CI engine LDW 502 M3 (Reggio Emilia, Italy)
Engine type	Online, four-stroke direct-injection
Number of cylinders	2
Bore × Stroke	72 mm × 62 mm
Displacement	505 cm^3
Max torque at rated speed 3000 rpm	26.2 N m
Compression ratio	22.8:1

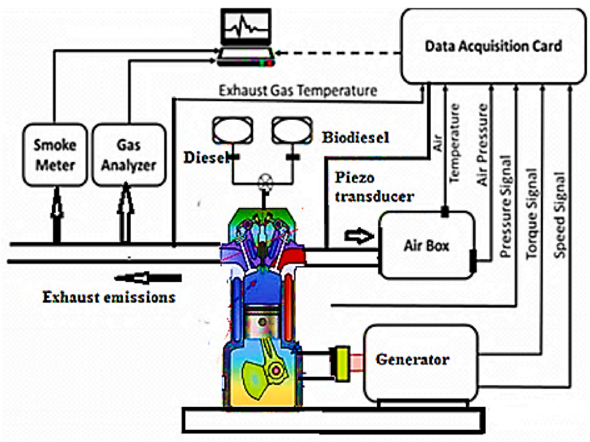

Fig. 1. Schematic diagram of the test rig.

$$NO_x \text{ (g/kWhr)} = 0.006636x\ NO_x \text{ (ppm)}$$

$$HC \text{ (g/kWhr)} = 0.002002x\ HC \text{ (ppm)}$$

Equation (1) shows the computation of the overall outcome of the experiment uncertainty.

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

Test rig's total uncertainty is being represented by W_R. The parameters R and x indicate the independent as well as dependent measurements, respectively. The overall uncertainty is evaluated at 3.1 %. ±1 ppm, ±1 ppm, ±0.01 % Vol, ±1 %, and ±1.5 % were found to represent the greatest levels of uncertainty for the metrics related to thermal efficiency, HC, NOx, CO, and smoke content, in that order. For engine speed, braking power, EGT, and BSFC, the most significant measurement errors were determined to be 0.15 %, 0.2, 0.85, 0.2, and 2.2 %, respectively. By adding together the parameter uncertainties using a predetermined formula, an overall uncertainty value was obtained.

$$\sqrt{(uTexh)^2 + (ubp)^{2\cdot} + (usfc.)^{2\cdot} + (uN.)^{2\cdot} + (uthers)^{2\cdot} + (u.CO)^{2\cdot} + (uHC)^2 + (uNOx)^{2\cdot} + (usmoke)^2}$$

$$= \sqrt{(0.2)^2 + (0.85)^2 + (2.2)^2 + (0.15)^2 + (1.5)^2 + (0.01)^2 + (1)^2 + (1)^2} = \pm 3.1\ \%$$

Where.

u_{bp}: Uncertainty of output power
$uT_{exh.}$: EGT uncertainty
$u_{N.}$: Engine speed uncertainty
$u_{CO.}$: CO emissions uncertainty.
u_{HC}: Uncertainty of HC concentrations.
u_{sfc}: Uncertainty in specific fuel consumption.
u_{ther}: Brake thermal efficiency uncertainty.
u_{NOx}: Uncertainty in NO_x emissions
u_{smoke}: Smoke concentration uncertainty

3. Results and discussions

3.1. Brake specific fuel consumption (BSFC)

Fig. 2 illustrates how the engine's brake specific fuel consumption is affected by the diesel and biodiesel blends. BSFC of biodiesel was greater than crude diesel for each load. Biodiesel needs more fuel for the engine to provide an equivalent power output because its calorific value is smaller. Biodiesel exhibits higher specific fuel consumption due to its increased viscosity, density, poor combustion characteristics, and lower volatility [38]. Volatility and viscosity of biodiesel increases are due to the frictional forces that induce atomization of fuel and heterogeneous mixing, leading to partial ignition and higher BSFC. Biodiesel and its blends leading to increased consumption of fuel and compensate for the decrease in brake output power, leading to an equivalent overall engine performance. It is possible to attribute crude diesel's higher brake specific fuel consumption to its reduced volatility and lower calorific value. Diesel oil burns more quickly and the fuel injection system sounds louder when using biodiesel because of its higher bulk

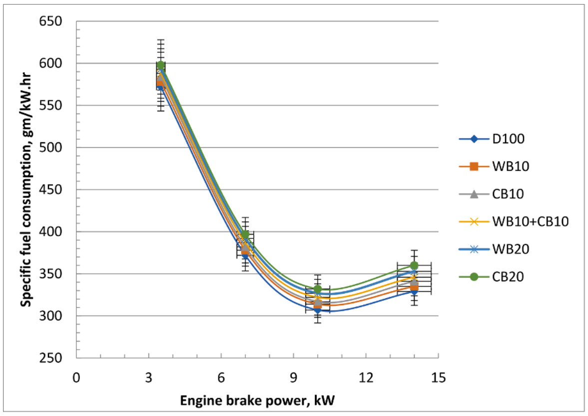

Fig. 2. Specific fuel consumption of biodiesel mixtures at engine load variation.

modulus. The biodiesel blend CB10+WB10 showed better characteristics than CB20 and WB20, including reduced kinematic viscosity, lowered density, decreased cetane number, and enhanced calorific value. When diesel fuel was used at full load, the BSFC for WB10, CB10, WB10+CB10, WB20, and CB20 increased by 2, 3.5, 5.5, 6, and 8.5 %, respectively. The findings were supported by the literature [37,39].

3.2. Brake thermal efficiency (BTE)

Fig. 3 illustrates the differences in brake thermal efficiency between diesel and methyl ester combinations. Under load variation, engine's output power and fuel consumption increased. Increase in methyl ester content in the test fuels led the BTE to decrease. BTE peaked and then started to drop as engine load rose. Lower engine loads use more fuel and produce more heat loss. Most notably, the greater gas cylinder temperature resulted in improved fuel combustion efficiency at higher engine loads. As engine load increased, so did brake specific fuel consumption owing to the frictional losses and rising fuel consumption [40]. The reduced BTE was due to the biodiesel's increased viscosity, poor combustion characteristics, and decreased volatility. Because biodiesel burns poorly and has low volatility, it has a reduced thermal efficiency. In addition to fuels with lower calorific values, atomization, and vaporization issues may be responsible for the loss in thermal efficiency related to diesel fuel. Methyl ester blend CB10+WB10 showed better properties than CB20 and WB20, including reduced viscosity, decreased cetane number, lowered density and enhanced calorific value. When comparing biodiesel with diesel oil at maximum output power, WB10, CB10, WB10+CB10, WB20, and CB20 had the biggest BTE reductions of 2.5, 4, 5, 6, and 9.5 %, respectively. The findings were supported by the literature [41,42].

3.3. Exhaust gas temperature (EGT)

Effect of the diesel and biodiesel mixtures on the engine's exhaust gas temperature is seen in Fig. 4. Increase of engine load leads to the increase of fuel consumption and cylinder temperature. Decrease of thermal efficiency and specific fuel consumption increase produce the greatest heat loss in exhaust. The lowered BTE was the result of biodiesel's increased viscosity, density, poor combustion characteristics, and decreased volatility about diesel oil. In addition to fuels with lower calorific values, atomization, and vaporiza-

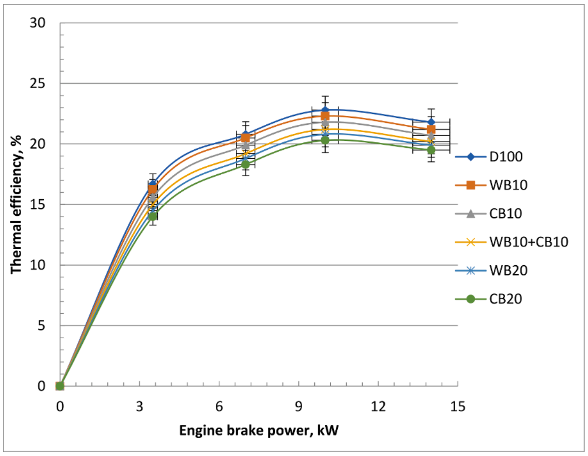

Fig. 3. Biodiesel blends' effects on brake thermal efficiency.

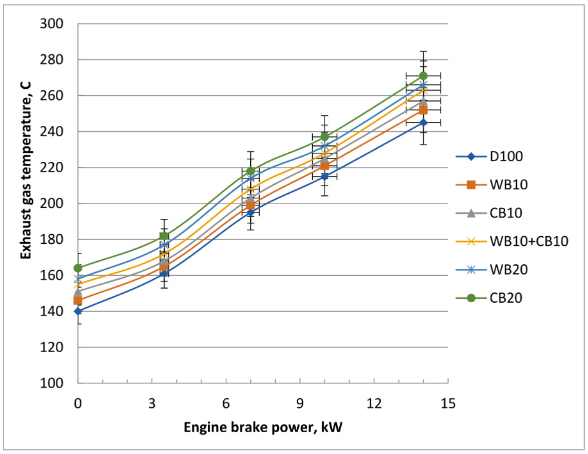

Fig. 4. Influence of methyl ester mixtures on EGT.

tion issues may be contributing to the loss in thermal efficiency and higher BSFC in comparison to crude diesel [22,25]. Compared to CB20 and WB20, the biodiesel mixture CB10+WB10 shown superior properties, such as decreased kinematic viscosity, decreased density, decreased cetane number, and increased calorific value. When comparing biodiesel to diesel oil at maximum output power, WB10, CB10, WB10+CB10, WB20, and CB20 had the biggest EGT increases of 3, 5, 7, 9 and 10 %, respectively. The results were supported by the previous works [40,42].

3.4. CO emission

Fig. 5 shows how output power affects carbon monoxide emissions for diesel and biodiesel blends. CO emissions were decreased with increasing load until they reach a minimum, beyond which they grow. CO emissions occur in environments with high air-to-fuel ratios because it is difficult to extract the oxygen required for oxidation of CO in the fuel. More amount of CO_2 is emitted by diesel fuel into the environment than biodiesel. The oxygen found in biodiesel molecules provides proof for this, as it enhances combustion and declines the possibility of fuel-rich zones formation. Increased ignition delay time lowers the possibility of complete or partial oxidation of the fuel. As a result, it has been shown that diesel oil produces higher emissions of incomplete combustion or CO. Longer ignition delay interval caused of diesel fuel about biodiesel. Due to a lack of secondary oxidation time, the biodiesel was forced out of the exhaust pipe before it could burn all the way through [20,25,30]. These explanations greatly explain why the diesel oil test fuel had higher CO emissions about biodiesel. Biodiesel mixture CB10+WB10 showed better properties than CB20 and WB20, including reduced kinematic viscosity, lowered density, enhanced calorific value and decreased cetane number. When diesel oil was utilized at peak load, the WB10, CB10, WB10+CB10, WB20, and CB20 had the largest reductions in CO emissions; the reductions were, in order, 0.5, 1.5, 2.5, 3, and 3.5 %. The results were confirmed by the literature [39–41].

3.5. NOx emission

Fig. 6 demonstrates the influence of different test fuels on the emissions of nitrogen oxides, with the engine brake power being varied. The primary factors contributing to the emission of nitrogen oxides (NOx) include oxygen concentration, residence time, temperature of cylinder, duration of combustion, chemical composition of fuel, and ignition delay. As engine power grows, so does

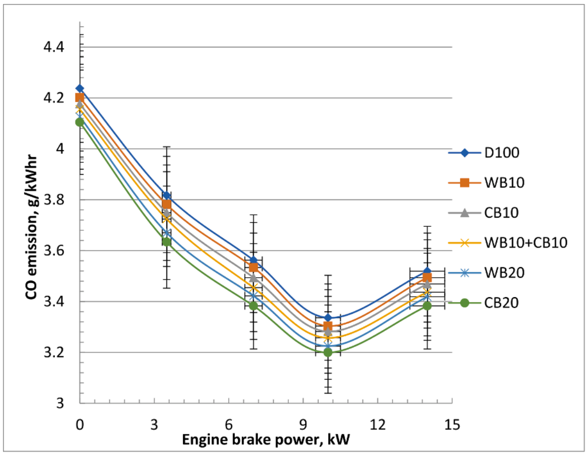

Fig. 5. CO concentrations of biodiesel blends at engine power variation.

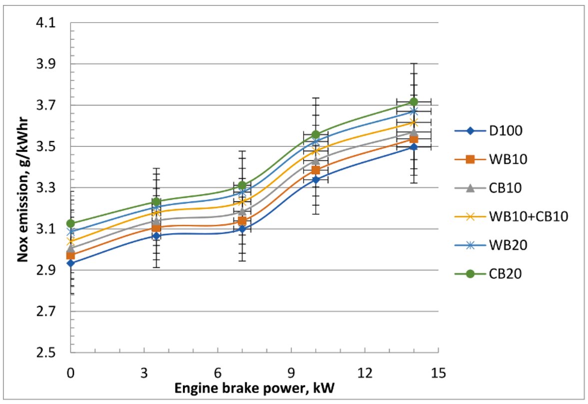

Fig. 6. NOx concentration of biodiesel mixtures at engine load variation.

the temperature of the combustion cylinder. During premixed combustion, NOx generation increases as the cylinder gas temperature rises and the fuel is added. The principal causes of the rise in NOx emissions at higher engine loads are higher fuel consumption and increased engine output power. Dissociated nitrogen reacts with the oxygen at higher cylinder combustion temperatures to form thermal NOx. All of these variables combined to raise the cylinder and the adiabatic flame temperatures, releasing more nitrogen oxide into the environment. Increased engine load was followed by the increased internal cylinder turbulence, resulting in a richer fuel-air mixture. When dissociated nitrogen and oxygen interact at higher combustion temperatures, thermal NOx is formed in the cylinder [18,25,30]. The surge in NOx concentrations was observed when biodiesel production was increased. Thermal NOx was formed by the cylinder's burning temperature and the oxygen in the surrounding air. Methyl ester mixtures produced more nitrogen oxides than diesel due to higher cylinder temperatures, adiabatic flame temperature and greater internal O_2 content. In comparison to CB20 and WB20, the biodiesel combination CB10+WB10 shown improved properties, such as decreased cetane number, increased calorific value, decreased kinematic viscosity, and dropped density. At 100 % engine load, the WB10, CB10, WB10+CB10, WB20, and CB20 biodiesel blends showed the greatest increases in NOx concentration compared to diesel oil: 1.5, 2.5, 3.5, 5, and 6.5 %, respectively. These findings were corroborated by Refs. [41,42].

3.6. HC emission

Fig. 7 demonstrates the variation in unburned hydrocarbon concentrations for diesel and methyl ester blends as engine output power changes. Every mixture showed rise in HC emissions as the engine's load increased and increase in fuel consumption. The reduced hydrocarbon concentrations observed at all loads result from the lack of oxygen during high-load engine running, which results in a rich fuel-air blend. High oxygen content of methyl ester contributes to this phenomenon. Biodiesel undergoes oxidation of the hydrocarbon fuel leading to a reduced production of hydrocarbons due to its higher content of oxygen as compared with conventional diesel oil [13,27,40]. When diesel oil is substituted with biodiesel with higher cetane number and lower ignition delay, amount of hydrocarbon emissions were decreased. Improved combustion and ignition was shown for biodiesel blends about diesel oil. The biodiesel combination CB10+WB10 demonstrated better properties than CB20 and WB20, including lower cetane number, improved calorific value, decreased kinematic viscosity, and decreased density. The biodiesel blends that showed the biggest reductions in hydrocarbon emissions at full load were WB10, CB10, WB10+CB10, WB20, and CB20, corresponding reductions of 6, 7, 10, 12, and 14 %. The results were corroborated by the literature [42,44].

3.7. Smoke emission

Fig. 8 indicates how smoke concentrations for diesel and mixtures of methyl ester vary with engine power. With increasing engine load, there is a rise in smoke emissions due to the rich fuel-air mixture created by an oxygen shortage. Increases in output power and fuel consumption increase smoke opacity. The methyl ester forms particles that oxidize more completely and burn more slowly due to its high oxygen content, which lowers smoke emissions. Diesel by itself produced more smoke than blends of biodiesel. Methyl ester's oxygen content improved ignition, reduced smoke generation and boosted combustion efficiency [12,20,30]. Biodiesel's oxygen concentration increases the amount of particle oxidation during diffusion combustion, increasing its ability to reduce smoke. In comparison to CB20 and WB20, the biodiesel combination CB10+WB10 showed superior characteristics, such as a reduced cetane number, an enhanced calorific value, lowered kinematic viscosity, and decreased density. When it came to diesel fuel, the largest reductions in smoke concentration were observed at peak loads of 6, 7.5, 8, 10.5, and 11 % for WB10, CB10, WB10+CB10, WB20, and CB20. The results were corroborated by earlier research [42,43].

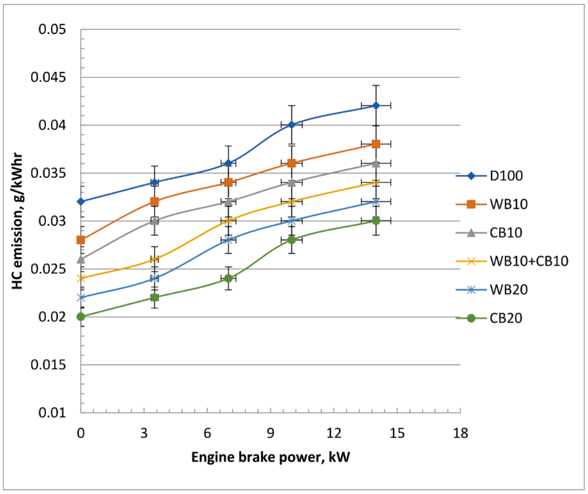

Fig. 7. HC concentrations of methyl ester combinations at engine output variation.

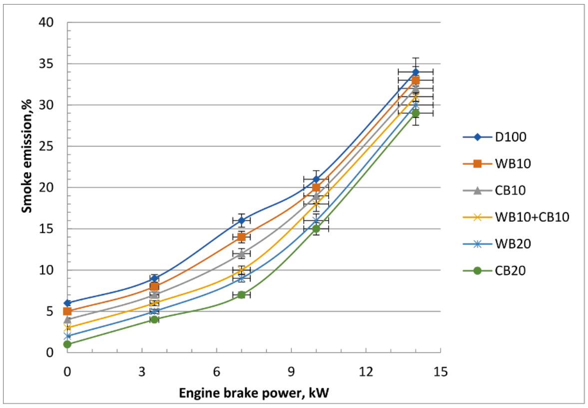

Fig. 8. Smoke emissions from mixtures of biodiesel at different loads.

3.8. In-cylinder pressure (P_{cy})

Fig. 9 indicates how the pressure inside the cylinders of a diesel engine over crank angle variation when the engine is running at full load, both when using pure diesel and different blends of biodiesel fuel. The trends in-cylinder pressure exhibited similarity across all fuels that were investigated. Biodiesel blends exhibit reduced peak cylinder pressure compared to diesel oil. Because methyl ester oil ignites more quickly than conventional diesel oil and has higher cetane number, the cylinder pressure is reduced. As the ignition delay was greater, more biodiesel was stored in the cylinder before ignition. When the fuel achieves the proper temperature and pressure, it burns efficiently. An extended ignition delay interval and more fuel collected allowed the diesel test fuel's peak cylinder pressure value to reach its maximum. Biodiesel fuel's oxygen concentration accelerates fuel droplet evaporation and reduces ignite delay. Biodiesel's larger bulk modulus causes the fuel injection system to sound faster and burn diesel oil more quickly. The decreased cylinder pressure may lead to insufficient atomization process, and decreased calorific value in the methyl ester blends about diesel. Due to its higher ignition rate compared to diesel fuel. Methyl ester consumed more of the fuel amount than diesel during the phase of diffusion [30,32,40]. The atomization and vaporization issues are exacerbated by the fact that biodiesel and its mixtures are denser and more viscous than diesel fuel, drastically altering spray characteristics. As a result, there is a potential that the two components may work together to extend the physical delay time, resulting in low peak cylinder pressure and inefficient burning. When the bulk modulus of biodiesel increases, diesel fuel burns faster, and the fuel injection system sounds early. Compared to CB20 and WB20, the methyl ester combination CB10+WB10 showed superior properties, such as a reduced cetane number, enhanced calorific value, lowered kinematic viscosity, and a decreased density. The unanticipated instability from cycle to cycle deteriorates diesel engine performance. Furthermore, fuels with high cetane number and short ignition delay shown advantageous effects by lowering cyclic variations in in-cylinder pressure. The load and biodiesel contents are the causes of the cylinder pressure fluctuations. Because of improved fuel-air mixing at higher velocities and air swirling, the increase in engine load conditions reduced the fluctuation in cylinder pressure. P_{max} ranges have a low coefficient of variation ($<$2.5 %) for both fuel types and load. Because of the low cetane number, cycle-to-cycle variance is associated with the properties of biodiesel fuel. The values of peak cylinder pressure at no load were 66.5, 66, 65.4, 65, 64.3 and 64 bar, respectively. The maximum cylinder pressure at 25 % of load were 67.1, 66.7, 66.2, 65.7, 65.2 and 64.7 bar, respectively. The values of peak cylinder pressure at 50 % of load were 67.5, 67, 66.7, 66.2, 65.7 and 65 bar, respectively. The highest cylinder pressure at 75 % of load were 68.4, 67.7, 67.2, 66.8, 66.2 and 65.6 bar, respectively. The values of

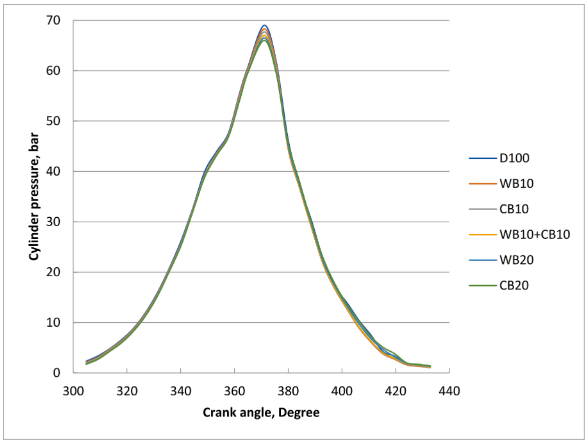

Fig. 9. Cylinder pressures of methyl ester blend at full load.

peak cylinder pressure at full of load were 69, 68.3, 67.5, 67, 66.5 and 66 bar, respectively. The cyclic variations of cylinder pressure are due to engine load and methyl ester percentage. Compared to full-load diesel fuel, WB10, CB10, WB10+CB10, WB20, and CB20 had the greatest decreases in peak P_{cy} as 1.5, 2, 2.3, 3.5, and 4.5 %, respectively. These findings were corroborated by Refs. [41,44].

3.9. Net heat release rate (HRR)

Fig. 10 depicts the heat release rate (HRR) for a mixture of biodiesel and diesel fuel across different crank angles and full load. The observed trends exhibited similarities between diesel and biodiesel blends. By increasing the content of methyl ester, blended biodiesel's peak heat release rates were decreased related to pure diesel. Biodiesel has reduced ignition delay and higher cetane value compared to conventional diesel fuel. In a premixed combustion phase, the highest rate of heat release (HRR) is generally lower because methyl ester blends have reduced fuel demand when compared to pure diesel fuel. Methyl ester mixtures have reduced heat release values due to their decreased calorific value compared with crude diesel. As the proportion of biodiesel added to diesel fuel increased, the heat release rate (HRR) and P_{cy} progressively were declined. Biodiesel has more density and viscosity than diesel fuel. Compared to diesel oil, biodiesel fuel consumes less fuel during the initial diffusion phase but more fuel during the premixed phase. Early burning is induced by the short-premixed combustion phase seen in biodiesel blends [10,15,23]. High-cetane biodiesel blends enhance the early stages of fuel preparation before combustion, resulting combustion in beginning of compression stroke. The methyl ester ignited more quickly, causing issues with atomization, fuel evaporation, and insufficient fuel-air mixing. Compared to diesel oil, methyl ester blends ignite more quickly due to the higher cetane number of biodiesel fuel. The combination of 20 % waste-cooking biodiesel and 10 % castor oil boosted densities, viscosities, and calorific values. The combination of biodiesels CB10+WB10 demonstrated better properties than CB20 and WB20, including lower cetane number, improved calorific value, decreased kinematic viscosity, and decreased density. When methyl ester mixtures were compared with diesel oil at 100 % output power, the greatest fall in peak heat release rate were 1.5, 2.5, 3, 4.5, and 5 % for WB10, CB10, WB10+CB10, WB20, and CB20, respectively. These conclusions were supported by the sources [40,44,45].

4. Comparative analysis

Table 3 compares diesel oil to the emissions, performance, and combustion properties of diesel engines for the WB10, CB10, WB10+CB10, WB20, and CB20.

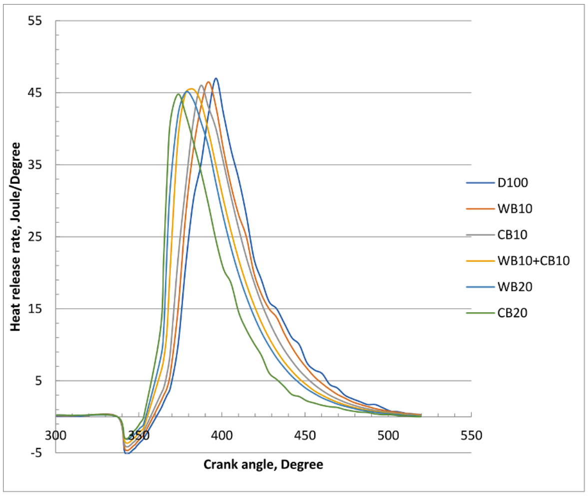

Fig. 10. Rate of heat release of methyl ester mixtures at crank angle variation.

Table 3
Variations in the emissions, performance, and combustion properties of a biodiesel blend at full load ((+) denotes an increase, while (−) denotes a decrease).

Relative change, %	CB10	WB10	CB10+WB10	CB20	WB20
BSFC	+2 %	+3.5 %	+5.5 %	+6 %	+8.5 %
BTE	−2.5 %	−4%	−5%	−6%	−9.5 %
EGT	+3 %	+5 %	+7 %	+9 %	+10 %
CO emission	−0.5 %	−1.5 %	−2.5 %	−3%	−3.5 %
HC emission	−6%	−7%	−10 %	−12 %	−14 %
NOx emission	+1.5 %	+2.5 %	+3.5 %	+5 %	+6.5 %
Smoke emission	−6%	−7.5 %	−8%	−10.5 %	−11 %
Peak cylinder pressure	−1.5 %	−2%	−2.3 %	−3.5 %	−4.5 %
Peak heat release rate	−1.5 %	−2.5 %	−3 %	−4.5 %	−5%

5. Conclusions

The experimental testing aimed to evaluate the emissions, combustion, and diesel engines performance utilizing waste cooking and castor biodiesel mixtures. This research aims to improve the physical and chemical characteristics of biodiesels by combining them with alternative feedstock, including castor oil and WCO, to improve combustion, emissions, and engine performance. Biodiesel was produced utilizing WCO and castor oil. Diesel oil and biodiesel was blended at volume ratios of 10 % and 20 %, respectively. ASTM standards were used to analyze the properties of pure biodiesel and diesel oil. This is a summary of the conclusions.

- The esterification and transesterification methods effectively produced castor biodiesel. WCO biodiesel was created by transesterification. Regular diesel fuel and biodiesels extracted from waste cooking and castor oils differ in viscosity, density, heating value and cetane number.
- The BSFC rose as the energy content of methyl ester decreased, while thermal efficiency decreased as the amount of biodiesel component increased. Biodiesel blends such as WB10, CB10, WB10+CB10, WB20, and CB20 showed the most increases in specific fuel consumption of 2, 3.5, 5.5, 6, and 8.5 % when diesel fuel was used at 100 % engine load; however, there were also decreases in thermal efficiency of 2.5, 4, 5, 6, and 9.5 %. The biggest increases in exhaust gas temperature about diesel oil at 100 % engine load were found to be 3, 7, 9, and 10 % for WB10, CB10, WB10+CB10, WB20, and CB20.
- When diesel oil was utilized at peak load, the WB10, CB10, WB10+CB10, WB20, and CB20 displayed the biggest reductions in CO emissions of 0.5, 1.5, 2.5, 3, and 3.5 %, respectively; in contrast, the NOx concentrations climbed to 1.5, 2.5, 3.5, 5, and 6.5 %. For WB10, CB10, WB10+CB10, WB20, and CB20, the biggest decreases in smoke concentration at peak load were 6, 7.5, 8, 10.5, and 11 %, respectively. The largest reductions in hydrocarbon emissions were seen in blends of biodiesel, with reductions of 6, 7, 10, 12, and 14 %, respectively.
- When comparing diesel fuel at full load, 1.5, 2, 2.3, 3.5, and 4.5 % showed the biggest declines in peak cylinder pressure, while 1.5, 2.5, 3, 4.5, and 5 % showed the highest drops in peak HRR for WB10, CB10, WB10+CB10, WB20, and CB20, respectively.
- Because of the hybridization of feedstocks with different characteristics, diesel engines running on these blends of 10 % castor and 10 % WCO hybrid biodiesel perform better, have improved combustion, and emit less emission. Using binary mixtures of biodiesels may be a viable way to enhance the fuel properties of biodiesels for use in CI engines. Hybrid castor and waste cooking methyl esters can greatly reduce exhaust pollutants while improving combustion and performance when used as a replacement fuel in diesel engines.

Future research may examine the thermodynamic, energy, economic, and exergy assessment of mixing binary and ternary biodiesels made from various feedstocks with conventional fuels. Modeling and optimization techniques should be used to account for the optimal biodiesel blend in order to obtain the desired effects on engine combustion.

CRediT authorship contribution statement

Aisha F. Fareed: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **A.S. El-Shafay:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **M.A. Mujtaba:** Writing – review & editing, Software, Formal analysis. **Fahid Riaz:** Writing – review & editing, Funding acquisition. **M.S. Gad:** Writing – review & editing, Methodology, Formal analysis.

Declaration of competing interest

I on the behalf of the all authors, declare that there is no conflict of interest and all the elements of the submission are also in compliance with the journal publishing ethics. By submitting this manuscript, the authors agreed that the copyright for their article should be transferred to this journal if the article is accepted for publication. The work contained within the research paper is our original contribution and has not been published anywhere.

Data availability

Data will be made available on request.

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