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Performance and emission characteristics of a diesel engine fuelled by biodiesel from black soldier fly larvae: Effects of synthesizing catalysts with citric acid

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ABSTRACT

Biodiesel has several environmental benefits, such as biodegradability, renewability and lower soot emissions. However, biodiesel has undesirable properties such as higher viscosity and density and low calorific value compared to petroleum diesel, resulting in high Brake Specific Fuel Consumption (BSFC), reduced Brake Power (BP) and increased NO_X emissions creating an environmental concerns in biodiesel development. This study investigated the effects of synthesizing transesterification catalysts (CaO and NaOH) with Citric Acid (CA) on the quality of biodiesel and biodiesel blends produced from Black Soldier Fly Larvae (BSFL) (Hermetia *Illucens*). The quality of biodiesel and blends was determined based on fuel properties, engine performance and emission composition characteristics. The tests were performed on a single-cylinder, four-stroke, Compression Ignition (CI) diesel engine at five loads at a constant speed of 1500 rpm. The results showed that synthesizing the catalysts with CA significantly affected the fatty acid profile of the biodiesel compared to physical fuel properties. B100 (pure BSFL biodiesel) exhibited higher BSFC by 10.57–13.97 % and lower BP by 4.21–7.83 % than diesel fuel. However, the Brake Thermal Efficiency (BTE) of biodiesel was higher than that of diesel fuel by 0.82–4.34 % at maximum load. Synthesizing catalysts with CA improved the viscosity of biodiesel by 0.93–2.81 % and effectively reduced NO_X, HC and Smoke opacity by 2.23–3.16 %, 4.95–5.83 % and 20.51–41.15 %, respectively.

1. Introduction

Biodiesel is a promising renewable fuel that can substitute conventional diesel fuels. Biodiesel is Fatty Acid Methyl Esters (FAME) derived by transesterification of triglycerides (animal fats or vegetable oils) in methanol with a catalyst or by non-catalytic supercritical transesterification [1]. Edible oils are commonly used for commercial biodiesel production, contributing to the high fuel cost [2]. Besides, using edible oil results in food vs. fuel competition by utilizing arable land. Using non-edible oils as feedstock for biofuels

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is gaining research interest to end the food vs. fuel criticism. Various non-edible oils for biodiesel production that have been reported as feasible for biodiesel production include microalgae, Waste Cooking Oil (WCO) [3], Jatropha oil [4], castor oil, waste plastic oil [5,6] and Black Soldier Fly Larvae (BSFL) oil [7].

Biodiesel production from microalgae, WCO and BSFL has added advantage in that it does not compete for land with crops and doubles as a waste treatment technique. Research has shown that BSFL have more than 30 % of lipid content which is more than that of microalgae indicating great potential for biodiesel production [8–10]. BSFL biodiesel differs from biodiesel derived from energy crops and microalgae in terms of fatty acid composition.

BSFL biodiesel has high composition of Saturated Fatty Acids (SFA) of over 70 % and low composition of unsaturated fatty acid of less than 30 % indicating its potential for production of high quality biodiesel [8,11,12]. On the other hand, energy crops such as rapeseed, peanut, linseed, sunflower and soybean have low amounts of saturated fatty and high composition of unsaturated fatty acids of over 70 % [13,14]. Previous studies have also shown that biodiesel with high composition of SFA results in lowers CO_2 and smoke emissions [15,16]. Increasing SFA in biodiesel has been reported to result in reduced NO_X emissions [16]. This indicates that biodiesel production from animal fat has potential to reduce engine exhaust emissions due to its low composition of unsaturated fatty acids [17].

Neat biodiesel can be used in CI engines without any modification. However, the physicochemical properties of biodiesel vary from those of diesel, indicating that the combustion and emission characteristics of the two fuels may have significant variations [18,19]. Most studies have shown that the performance characteristics of an engine fuelled by biodiesel, such as Brake Thermal Efficiency (BTE) and Brake Power (BP), are lower than those of diesel, while the Brake Specific Fuel Consumption (BSFC) is remarkably high [20–22]. However, opposite results showing improved BTE from biodiesel in comparison to diesel have also been reported by Yilmaz et al. [23].

Research on emission characteristics of biodiesel has received controversial reports, with most studies indicating reduced CO, CO_2, HC and particulate matter while NO_X emissions are increased compared to diesel fuel [24–30]. On the other hand, some studies have reported higher HC emissions [20,23], lower NO_X emissions [23], and increased CO_2 emissions [31]. Kamarulzaman et al. [7] reported lower NO_X emissions from BSFL biodiesel due to poor fuel atomization resulting in reduced heat release rate. On the contrary, Cheng et al. [32] reported higher NO_X emissions form BSFL biodiesel citing longer combustion period of biodiesel due to higher oxygen content compared to diesel fuel. There is therefore need to further investigate on methods and processes that will control and lower emissions from BSFL biodiesel.

Blending biodiesel with higher alcohols such as pentanol, ethanol, butanol and propanol has been reported to improve the BTE and slightly reduce NO_X emissions in diesel engines [27]. Addition of pentanol to safflower biodiesel was reported to lower HC, smoke and CO emissions while CO_2 emissions were increased [22]. An experimental comparison of vegetable oil biodiesel blend with pentanol and propanol demonstrated that pentanol slightly reduces BSFC while propanol was reduced the NO_x emissions [23]. However, high composition of alcohols in biodiesel blend result in increased CO and HC emissions due to their low cetane numbers, increased oxygen content and high latent heat of evaporation [20,23].

Higher NO_X emissions from biodiesel than diesel fuel are one of the environmental concerns in biodiesel development. Few researchers have reported the possibility of lowering NOx emissions. Hawi et al. [33] reported that iron-doped cerium nanoparticles reduced NO_X emissions by 17.5 % and explained that the nanoparticles reacted with NO, reducing it to nitrogen. Similarly, Suhel et al. reported than ZnO nanoparticles improved the engine performance and lowered NOx emissions of biodiesel derived from waste plastic oil [5]. However, additives have been linked to increased CO_2 emissions, which directly impact Green House Gases (GHG). Shekofteh et al. [34] demonstrated that carbon nanotube additives improve engine performance and increase NO_X emissions by 5.78–9.64 %. Similar findings were also reported by Srinivasan et al. [29] and Elnajjar et al. [35].

Current research on biodiesel inquest on cost-effective feedstock, catalyst development and production methods to improve the qualities of biodiesel and its engine performance to compare closely to those of diesel fuel [18,36,37]. Recent studies are investigating non-catalytic supercritical transesterification for biodiesel production from waste resources such as microalgae. These methods have reduced the number of steps in biodiesel production and also eliminates the challenges of solvent and catalyst separation [38]. However, these methods are limited for commercialization due to high operating temperature above 350 °C and pressure above 20 MPa [38–40]. Besides, the high production temperatures degrade the biodiesel posing a major drawback to the technology [38].

Catalyzed transesterification is cost-effective and therefore used for commercial biodiesel production [41,42]. This suggests the need to develop effective catalyst for biodiesel production that can be used in transesterification of oil from waste resource feedstock to lower the cost of biodiesel and environmental pollution.

Synthesizing catalysts with CA improves the quality of biofuels in methanation and biodiesel production [43,44]. Catalysts synthesized with CA have also been reported to be effective in hydrocarbon oxidation [45], CO_2 adsorption in hydrogen production [46] and improving the activity of catalysts in methane production [47,48]. Although several studies have investigated and compared the use of CA in the development of heterogeneous catalysts with improved biodiesel yield and quality, the effects of the modified catalysts on the quality of exhaust emissions have not been adequately reported.

This research aims to develop heterogenous catalysts for biodiesel production form waste resources such as BSFL with improved quality and reduced emissions to the environment. In this study, the effects of synthesizing transesterification catalysts (NaOH and CaO) with CA on fuel quality, engine performance and exhaust emission composition of biodiesel derived from BSFL are experimentally determined. The fuel samples of biodiesel, diesel and biodiesel blends with diesel and propanol are tested in a CI engine for performance and exhaust emissions characteristics.

2. Methods

2.1. Catalysts preparation

The catalysts (CaO/CA and NaOH/CA) were prepared by synthesizing CaO (AR Grade, 98 %) and NaOH (AR Grade, 98 %) with CA by impregnation and precipitation, respectively, as reported by Kathumbi et al. [49]. First, CaO and NaOH were synthesized with 40 % and 130 % (wt.%) of CA, respectively, in 50 ml of deionized water at 80 °C. This was followed by drying in the oven at 130 °C for 12 h. After drying, the mixture was calcined in a furnace at 900 °C and 600 °C for CaO/CA and NaOH/CA, respectively, for 4 h. The catalysts preparation procedure is shown in Fig. 1.

The chemical composition, morphology, structural and crystalline properties of CaO/CA and NaOH/CA are reported in our previous study [49].

2.2. Oil extraction and transesterification of BSFL oil

Biodiesel used in this study was produced from BSFL that were reared at Jomo Kenyatta University of Agriculture and Technology. After hatching, the larvae were fed on processed wheat meal as a starter feed for five days and, after that, reared on unprocessed kitchen waste food from restaurants. The BSFL were harvested after 28 days of rearing, then washed, deactivated in hot water and dried in an oven at 80 °C. The dry BSFL biomass was ground using a kitchen blender before oil extraction. Oil was extracted from BSFL biomass by solvent extraction method using n-hexane in a ratio of 1:3 (Fig. 2a). The mixture was kept in a shaker at 300 rpm for 20 min and then left in situ overnight. Next, oil and solvent were separated from the biomass in a funnel separator (Fig. 2b). The oil was then recovered from the solvent using a rotary evaporator (Fig. 2c). The oil extraction process is shown on Fig. 2.

Two-step esterification followed by transesterification process was adopted in this study for biodiesel synthesis following a method described by Su et al. [50]. First, esterification was carried out by heating 0.5 L BSFL oil in 0.8 L methanol with 1 vol% H_2SO_4 as the catalyst at 100 °C for 1 h under stirring. After cooling, the mixture was left in a separator funnel overnight to separate the oil, methanol and catalyst (Fig. 3). Next, transesterification was carried out by reacting esterified oil with 1.8 wt% of the modified catalysts and methanol (equal volume to oil) at 90 °C for 1 h under stirring.

For each catalyst, five samples of biodiesel and biodiesel/diesel/propanol blends were prepared, namely: B100, B20, B10, B5 and B2.5. For example, B20 represented: 20 vol% biodiesel, 70 vol% diesel and 10 vol% propanol, while B100 represented pure/neat biodiesel from BSFL. For all blends (B2.5, B5, B10 and B20), propanol was maintained at 10 vol%, as reported by Yilmaz et al. [23], to prevent phase separation and increased HC and CO emissions. Propanol was chosen to improve the basic properties of the fuel and because it has minimal effects on the emission composition of the fuel blend [23]. The biodiesel/diesel/propanol blends were mixed using a magnetic stirrer at 1200 rpm for 6 min and then stored in closed bottles.

Samples were prepared and tested in triplicates for fuel properties and engine performance characteristics. The results of biodiesel and biodiesel blends performance on diesel engine were compared to those of diesel fuel. Data were computed as mean value from three replicates. Excel spreadsheet was used for analysis of the results.

2.3. Fuel testing

The fuel properties, engine performance and emission composition analysis of biodiesel produced by the three catalysts (CaO/CA, NaOH/CA and CaO) were determined and compared to those of petroleum diesel. The equipment and apparatus used to determine the density, viscosity, calorific value, cetane number, iodine value, acid value and refractive index of the biodiesel, biodiesel bends and diesel are presented in Table 1.

Gas Chromatography Mass spectrometer (GC-MS) (Shimadzu QP2010SE) fitted with BPX5 capillary column was employed to

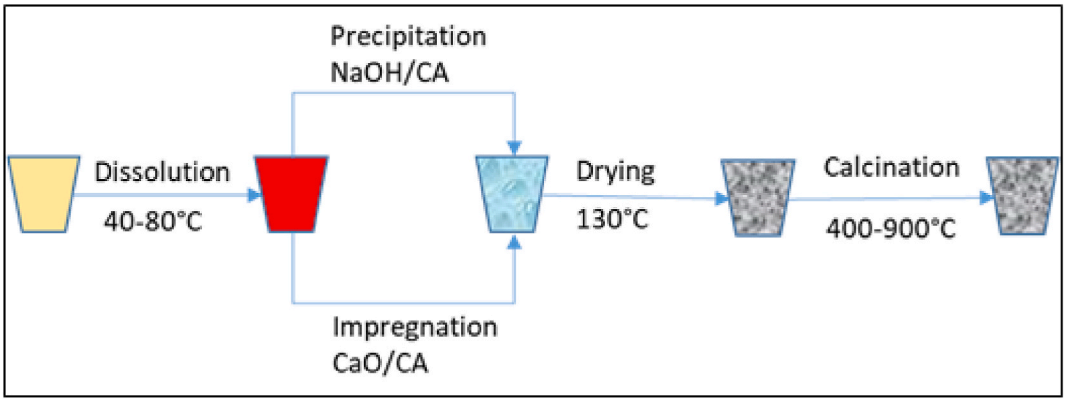

Fig. 1. Catalyst preparation process.

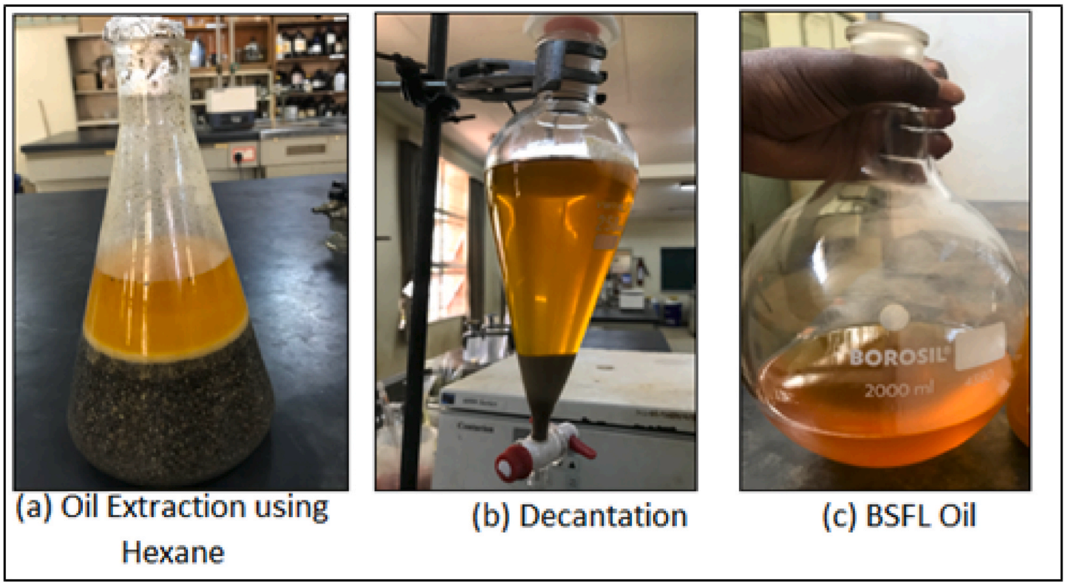

Fig. 2. Bsfl oil extraction process.

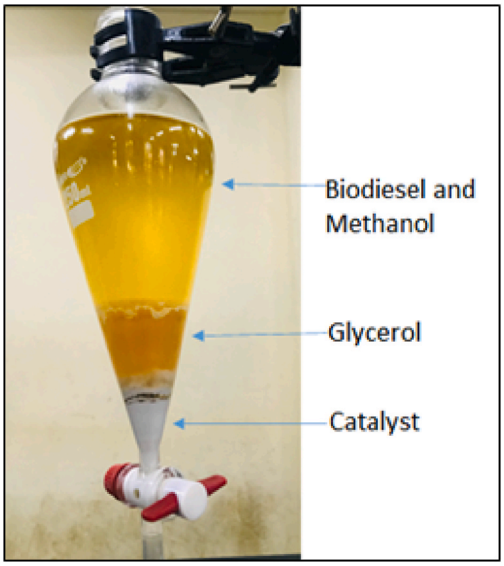

Fig. 3. Separation of biodiesel and methanol from glycerol and catalyst.

Table 1
Test methods for fuel physicochemical properties.

Properties	Apparatus	Method	Source
Density at 40 °C (kg/m^3)	Pycnometer	ASTM D7042	[51]
Kinematic viscosity at 40 °C (mm^2/s)	Redwood viscometer	ASTM D7042	[51]
Calorific Value	Bomb calorimeter (CAL2K)	ASTM D240	[52]
Iodine Value (g I_2/100g)	Titrimetric	AOAC (920.158)	[53]
Acid Value (mg KOH/g)	Titrimetric	AOAC (993.20)	[53]
Cetane Number	Calculated	Relative index	[54]

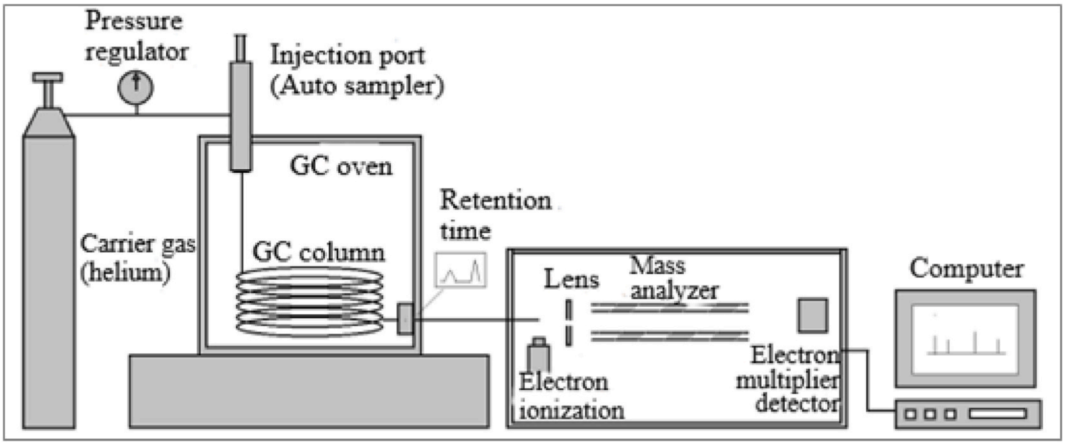

Fig. 4. Block diagram of GC-MS set-up.

Table 2
Specifications of gas chromatography mass spectrometer.

Parameter	Specification
Carrier gas	Helium
Column head pressure	11.3 psi
Column dimension	BPX 5, 30.0 length × 0.25 μm ∅ × 0.25 mm thickness
Linear velocity	38.2 cm/s
Detector temperature	280.0 °C
Injector	250.0 °C
Final temperature	280.0 °C (hold for 10 min)

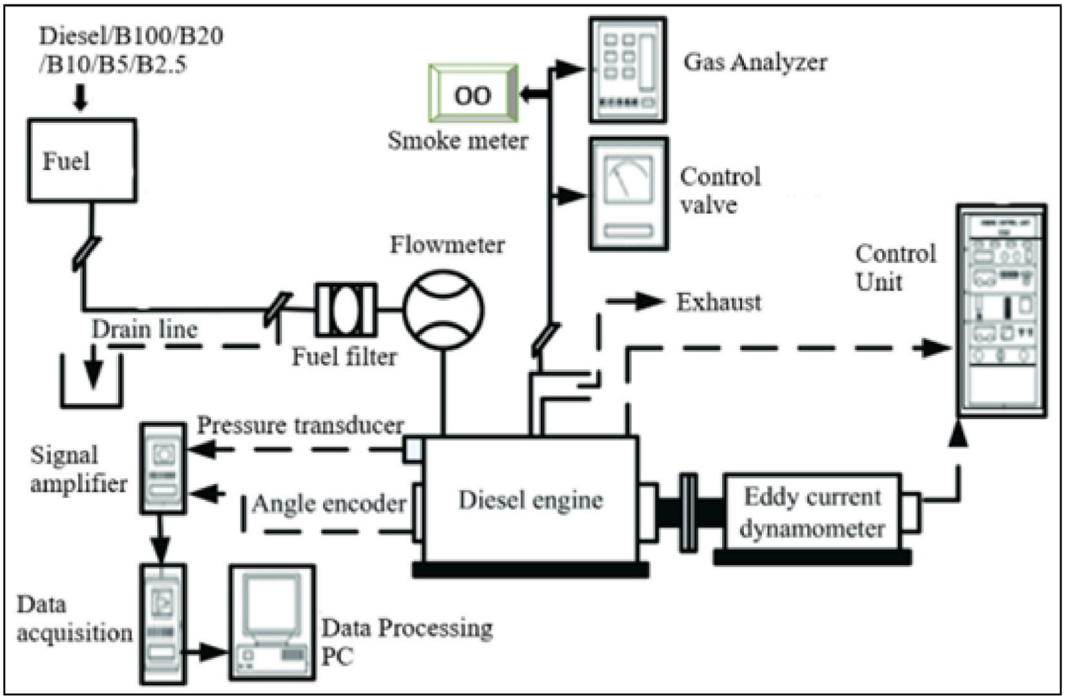

Fig. 5. Experimental set-up for engine performance tests.

determine the fatty acid composition of the biodiesel and biodiesel blends. The GC-MS set up and operating conditions are presented in Fig. 4 and Table 2, respectively.

2.4. Experimental SetUp

Engine tests were performed in a single-cylinder diesel engine equipped with an eddy current dynamometer to provide brake load at a constant speed of 1500 rpm. The load was varied from 0 to 12 kg with recording at 0, 3, 6,9 and 12 kg. First, the engine was warmed up using diesel fuel for 10 min and recordings were taken when oil temperatures reached 80 °C. After testing each sample the engine was flashed with diesel fuel and switch off for 90 min before testing the next sample. The performance indicators analyzed from the engine test included: BSFC, BTE and BP. For every sample analyzed, the exhaust gases were passed through the probe of a Testo 350 gas analyzer to determine the levels of CO, CO_2, HC and NO_X emission, while smoke opacity was measured using a Banzai DSM 10 smoke meter. Although engine combustion characteristics such as cylinder pressure, heat release rate and cylinder temperatures provide more insights on the fuel performance, there parameters were not analyzed in this study due to experimental limitations. The aforementioned engine performance and emission composition analysis were used to compare the performance of the fuel samples. The engine set up, engine specifications and emission analyzers used in this study are shown in Fig. 5, Tables 3 and 4, respectively.

3. Results and discussion

3.1. Fuel properties

Biodiesel's chemical and physical fuel properties depend on the feedstock type, fatty acid composition, and type of catalysts used in the transesterification and production method [36,55,56]. The fuel properties of the biodiesel produced from BSFL oil using different catalysts and the derived biodiesel blends are presented in Tables 5 and 6, respectively.

The fuel properties of biodiesel derived from BSFL (Table 5) that are fed on kitchen waste met the standard specifications for EN12412, indicating the feasibility of producing quality biodiesel from waste resources. These results agree with researchers that have reported the properties of biodiesel from BSFL to be within the recommended limits for biodiesel [32,57,58]. The catalysts synthesized with CA improved the viscosity and calorific value of biodiesel by 2.81 % and 0.11 % for NaOH/CA and 0.93 % and 0.07 % for CaO/CA, respectively, as presented in Table 5. These results indicate that the type of catalysts had minimal impact on the physical properties of biodiesel.

The catalysts synthesized with CA lowered the total Saturated Fatty Acids (SFA) content (0.27–0.28 %) and Polyunsaturated Fatty Acids (PUFA) (7.94%–25.70 %), while Monounsaturated Fatty Acids (MUFA) increased by (3.12%–7.56 %) indicating that synthesizing catalysts with CA was more effective in reducing the degree of PUFA in biodiesel (Table 5). These results agree with the study by Allami & Nayebzadeh [36] who assessed the effect of homogenous and heterogeneous catalysts on biodiesel physical and chemical properties and reported that the type of catalysts had a significant influence on the fatty acid profile of biodiesel from WCO.

The physical properties of biodiesel and biodiesel blends vary significantly from those of diesel fuel, as presented in Table 6. Biodiesel blends were observed to have a higher viscosity, density and cetane than diesel fuel. The viscosity, density and cetane number of B100 (Table 5) was higher by 60.65–65.11 %, 2.41–2.69 % and 11.49–11.65 % compared to diesel fuel (Table 6). The high density and viscosity of biodiesel have been linked to increased engine fuel consumption, lower engine efficiency and increased NO_X emissions [22,27].

The high cetane number of biodiesel from BSFL is attributed to the low composition of MUFA and PUFA. Giakoumis & Sarakatsanis [59] reported that cetane number is influenced by both the physical and chemical composition of fuels and that it increased with a decrease in the degree of unsaturation. Besides, an increase in cetane number shortens the ignition period delay resulting in lower soot emission from diesel engines [60,61]. This behavior shows the potential of BSFL biodiesel in lowering particulate matter emissions. Biodiesel from BSFL was observed to possess a very high composition of SFA (more than 70 %). Oxygen fuel content increases with increased SFA content and results in improved engine combustion characteristics [15,62].

Table 3
Engine specification.

Type	IC diesel engine, water cooled
Number of cylinders	1
Number of strokes	4
Stroke length	110 mm
Cylinder diameter	87.5 mm
Connecting rod length	234 mm
Injection orifice diameter	20 mm
Dynamometer arm length	185 mm
Compression ratio	17.5:1
Injection timing	25° BTDC
Rated Power	3.5 kW
Rated Speed	1500 RPM
Eddy dynamometer	0–16 kg

Table 4

Specification, range and accuracy for the emission composition analysers.

Device specification	Range	Accuracy
Gas Analyser Testo 350		
Carbon monoxide (CO)	0–9.99 (vol%)	±0.02 %
Carbon dioxide (CO_2)	0–19.99 (vol%)	±0.03
Hydrocarbon (HC)	0-10,000 ppm	±20 ppm
Oxides of nitrogen (NO_X)	0-5000 ppm	±10 ppm
Smoke meter: Banzai DSM-10		
Smoke intensity	0- 100 opacity (%)	±1 %

Table 5

Physiochemical Properties of BSFL oil and Biodiesel Synthesized by Different Catalysts.

Properties	Unit	BSFL oil	Biodiesel			EN14214 limit	Diesel
			NaOH/CA	CaO/CA	CaO		
Physical properties							
Kinematic Viscosity at 40 °C	mm2/s	7.88	4.14	4.22	4.26	2.5–6.0	2.58
Density at 40 °C	kg/m3	882.47	866.24	867.01	867.82	860–900	845.8
Calorific Value	MJ/kg	39.02	39.22	39.21	39.18		43.44
Refractive Index		1.4667	1.4566	1.4565	1.4566		1.4623
Iodine Value	g I2/100g	92.38	89.86	86.44	87.06	120 max.	n.d
Cetane Number		56.72	58.15	58.11	58.19	51 min.	52.12
Chemical properties							n.d
Caproic acid (C10:0)	wt.%	1.09	2.05	0.37	2.08		n.d
Lauric acid (C12:0)	wt.%	28.54	39.16	38.14	40.47		n.d
Myristic acid (C14:0)	wt.%	5.02	9.68	11.47	10.07		n.d
Palmitoleic acid (C16:1)	wt.%	9.54	8.63	7.46	8.79		n.d
Palmitic acid (C16:0)	wt.%	21.71	15.11	18.06	12.69		n.d
Heptadecanoic acid (C17:0)	wt.%	3.92	3.88	2.71	4.38		n.d
Stearic acid (C18:0)	wt.%	0.9	2.98	2.11	3.37		n.d
Oleic acid (C18:1)	wt.%	21.22	13.48	13.66	11.69		n.d
Linoleic acid (C18:2)	wt.%	6.92	4.02	4.98	5.41		n.d
Others	wt.%	1.14	1.01	1.04	1.05		100
Saturated content	wt.%	61.18	72.86	72.86	73.06		n.d
monounsaturated content	wt.%	30.76	22.11	21.12	20.48		n.d
polyunsaturated content	wt.%	6.92	4.02	4.98	5.41		n.d
Ester content	%	95.74	98.66	98.82	98.66	96.5	n.d

Table 6

Physiochemical Properties of Diesel and Biodiesel Blends Produced using NaOH/CA.

Properties	Unit	B2.5	B5	B10	B20	Diesel
Physical Properties						
Kinematic viscosity at 40 °C	mm^2/s	2.58	2.78	3.13	3.51	2.58
Density at 40 °C	kg/m^3	854.66	854.68	858.12	860.14	845.8
Calorific Value	MJ/kg	43.33	42.88	42.24	41.54	43.44
Refractive index		1.4602	1.4593	1.4588	1.4577	1.4623
Cetane Number		52.43	52.92	53.84	55.04	52.12
Chemical Properties						
Caproic acid (C10:0)	wt.%	n.d	n.d	n.d	n.d	n.d
Lauric acid (C12:0)	wt.%	4.02	5.26	12.48	19.17	n.d
Myristic acid (C14:0)	wt.%	n.d	1.68	3.77	3.99	n.d
Palmitoleic acid (C16:1)	wt.%	n.d	0.98	2.07	2.1	n.d
Palmitic acid (C16:0)	wt.%	1.98	2.38	6.39	8.25	n.d
Heptadecanoic acid (C17:0)	wt.%	n.d	n.d	2.04	2.73	n.d
Stearic acid (C18:0)	wt.%	1.61	1.78	4.83	6.3	n.d
Oleic acid (C18:1)	wt.%	n.d	n.d	0.93	0.95	n.d
Linoleic acid (C18:2)	wt.%	n.d	n.d	1.44	1.83	n.d
FAME	wt.%	7.61	12.08	33.95	45.32	n.d
Alkanes	wt.%	90.74	86.57	65.32	54.1	99.22
Other compounds	wt.%	1.65	1.35	0.73	0.58	0.78

n.d = not detected.

As expected, the FAMEs composition in biodiesel blends increased with an increase in biodiesel content in the blend, indicating improved oxygen content and lubricity of the fuel blends. Alkanes (hydrocarbons) formed the highest composition of the biodiesel blends. The alkanes detected in biodiesel blends included: dodecane ($C_{12}H_{24}$), undecane ($C_{11}H_{24}$), tetradecane ($C_{14}H_{40}$), tridecane ($C_{13}H_{28}$), pentadecane ($C_{15}H_{32}$), hexadecane ($C_{16}H_{34}$), heptadecane ($C_{17}H_{36}$), eicosane ($C_{20}H_{42}$), docosane $C_{22}H_{46}$) tricosane ($C_{23}H_{48}$) and heneicosane ($C_{21}H_{44}$). The improved, calorific value of biodiesel blends can be attributed to the presence of alkanes. However, alkanes have adverse environmental impacts due to increased CO and particulate matter emissions [63]. Other compounds present in very small quantities included carbonic acid, butyric acid, and naphthalene.

3.2. *Engine performance*

3.2.1. *Brake Specific Fuel Consumption (BSFC)*

BSFC indicates the fuel consumed by an engine per unit power output. Biodiesel has higher viscosity, density and lower calorific value than diesel fuel resulting to higher BSFC [27]. The effect of blending biodiesel produced from BSFL using different catalysts with petroleum diesel on BSFC at varied engine load is presented in Fig. 6.

The investigation of engine load variation against BSFC yielded interesting results. Initially, at a load of 0 kg, the BSFC was notably high, and ranged between 6.16 and 6.17 kg/kWh. Subsequently, with an increase in load, the BSFC exhibited a sharp decline, reaching a minimum value at 6 kg (0.72–0.82 kg/kWh). This significant reduction suggests an optimal engine load at 6 kg. As the load was further increased to 12 kg, a slight increase in BSFC was observed (0.91–0.93 kg/kWh). This trend aligns with the findings of Emiroğlu & Şen [20] who reported 0.27 MPa as the optimum load within a range of 0.09–0.36 MPa. Their study highlighted that low engine loads resulted in higher BSFC due to low premixed combustion phase. Similarly, Mohamed et al. [37] observed a similar behavior, marking 75 % of full load as the optimum engine load. The initial high BSFC, followed by a decline and thereafter a slight increase may be attributed to friction and other losses impacting the engine mechanical efficiency, as discussed in Section 3.2.2.

The application of neat biodiesel (B100) demonstrated higher BSFC compared to diesel fuel, as evident in Fig. 6a. On average, B100 exhibited a 10.57 % increase in BSFC at maximum load. This result can be attributed to the higher density and lower calorific values of biodiesel. Furthermore, investigating the influence of catalysts synthesized with calcium oxide (CaO) and sodium hydroxide (NaOH) on BSFC did not yield a definitive outcome. Notable differences were primarily observed at high engine loads, where NaOH/CA displayed a 15.29 % and 2.98 % reduction in BSFC compared to CaO, respectively. Similarly, for CaO/CA, the BSFC was 2.98 % and 1.07 % lower than CaO at 9 kg and 12 kg loads, respectively.

Investigation into the effect of biodiesel content in fuel blends on BSFC showcased intriguing findings (Fig. 6b). B2.5 and B5 exhibited slight reductions in BSFC by 4.65 % and 1.98 %, compared to pure diesel fuel. This outcome is likely attributed to enhanced fuel combustion and increased oxygen content within the biodiesel blend. Notably, the introduction of biodiesel blends brought about a successful enhancement in fuel BSFC, corroborating earlier research [60]. The reduction in BSFC in biodiesel blends was not as significant as in diesel fuel. This outcome could be attributed to the presence of propanol in the biodiesel blends as opposed to higher alcohols like ethanol or methanol, which have been reported to adversely affect BSFC due to their lower heating values [20,22,64].

3.2.2. *Brake Thermal Efficiency (BTE)*

The variation in BTE with the increased engine load is presented in Fig. 7.

BTE signifies the conversion of chemical energy to mechanical energy, which is influenced by a combination of factors such as: fuel properties, air-fuel ratio, combustion process and engine load dynamics [22].

In the context of this study, BTE exhibited intriguing variations. Initially, at 0 kg load, BTE ranged from 1.58 % to 1.60 %. Subsequently, as the load increased, BTE experienced a progressive rise, culminating in a peak range of 11.66 %–11.92 % at a 6 kg load. Beyond this optimal point, BTE demonstrated a decrease to 9.68 %–10.10 % at a 12 kg load, aligning with the optimum engine load identified in Section 3.2.1. This trend is attributable to the increase in power with increase in load until a maximal BTE is achieved,

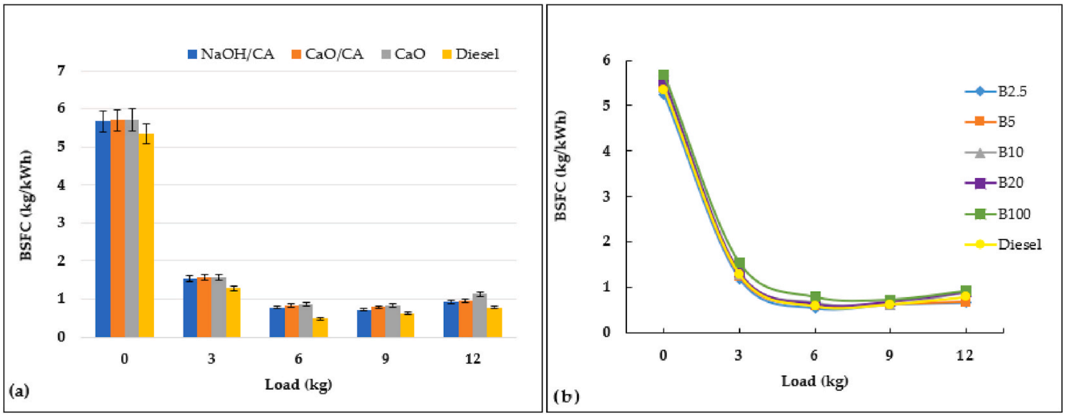

Fig. 6. Comparison of BSFC from diesel with (a) biodiesel produced by NaOH/CA, CaO/CA and CaO (b) biodiesel and biodiesel blends.

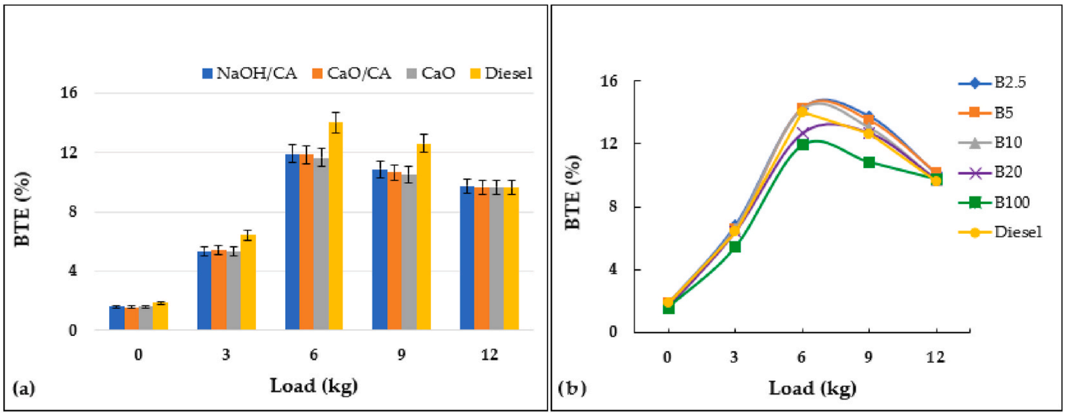

Fig. 7. Comparison of bte of diesel fuel to that of (a) B100 produced by NaOH/CA, CaO/CA and CaO (b) biodiesel and biodiesel blends.

after which further load increments lead to a decline in BTE. The reduction in BTE post-peak can be attributed to augmented mechanical friction, inertia forces, and heat losses stemming from rotating components [30,31]. It's worth noting that the BTE values in this study are lower than those reported for biodiesel and diesel fuels (ranging from 6.5 to 27.6 %) [20,29,37], potentially due to engine wear and losses.

Comparing BTE between neat biodiesel and diesel fuel unveiled notable insights. Generally, the BTE of neat biodiesel was lower than that of diesel fuel, except at maximum load where biodiesel exhibited a higher BTE. Specifically, the BTE of biodiesel catalyzed by NaOH/CA, CaO/CA, and CaO exceeded diesel fuel BTE by 4.8 %, 1.29 %, and 0.46 %, respectively, at maximum load, as depicted in Fig. 7a. Similar findings highlighting improvement in BTE at higher loads for biodiesel derived from animal fat have been documented [60,65]. These results indicates the potential efficacy of BSFL biodiesel in heavy-load machinery applications. Moreover, the synthesis of catalysts with CA led to improved BTE of the biodiesel. At maximum load, the BTE of biodiesel was improved by 4.34 % and 0.82 % for NaOH/CA and CaO/CA, respectively, compared to that of CaO. This enhancement could be linked to the improved viscosity of the biodiesel, as viscosity impacts combustion efficiency [66]. Kodate et al. [66] reported that lowering the viscosity of biodiesel by preheating enhanced both BTE and BSFC.

Blending biodiesel with diesel and propanol had a positive impact on BTE of the biodiesel, as shown in Fig. 7b. This result could be attributed to the improved viscosity of the fuel blend. Notably, BTE improvements were prominent for B2.5, B5, and B10, surpassing diesel fuel by 5.24 %, 5.65 % and 1.61 %, respectively, at maximum load. These results agree with Selvakumar & Alexis [65] who reported that B10 from animal fat exhibited higher BTE than diesel fuel. These results suggest that lower volume ratios of biodiesel (B2.5-B10) in the blend can be adapted by transportation sector to improve diesel engine performance. Similar to B100, B20 was observed to have higher BTE at higher engine loads of 9 kg and 12 kg by 0.63 % and 1.30 %, respectively, compared to diesel fuel. This improvement could result from additional lubrication and oxygen content of the biodiesel that enhanced the fuel combustion [24].

3.2.3. *Brake power (BP)*

Brake power indicated the actual power at the crankshaft and was observed to increase with the increase in engine load. The brake

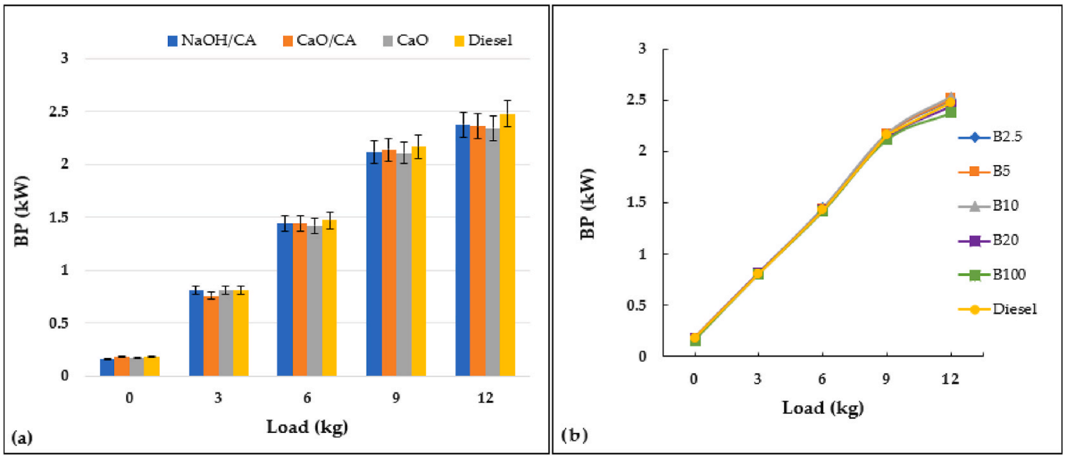

Fig. 8. Engine Brake Power vs. Load for (a) Biodiesel Synthesized Using NaOH/CA, CaO/CA and CaO in Comparison to Diesel Fuel (b) Biodiesel, Biodiesel Blends and Diesel.

power for neat BSFL biodiesel and diesel fuel and biodiesel and its blends at varied engine loads is presented in Fig. 8(a and b).

Analysis of the BP provided insights into the performance of BSFL biodiesel in comparison to diesel fuel. As illustrated in Fig. 8a, biodiesel demonstrated slightly lower brake power than diesel fuel. At maximum load, the reduction in BP was 4.21, 5.08 and 7.83 % for B100 from NaOH/CA, CaO/CA and CaO catalysis, respectively, compared to diesel fuel. Remarkably, synthesizing catalysts with CA exhibited improvements in the BP, particularly at higher engine loads exceeding 3 kg. Notably, at maximum load (12 kg), the engine brake power of biodiesel synthesized by NaOH/CA and CaO/CA improved by 3.47 % and 2.61 %, respectively, compared to biodiesel produced by CaO.

The analysis of brake power in BSFL biodiesel blends and diesel fuel revealed intriguing trends. At lower loads (0–6 kg), as depicted in Fig. 8b, brake power levels were comparable between biodiesel blends and diesel fuel. However, as the load surpassed 6 kg, the biodiesel blends (B2.5, B5, and B10) exhibited elevated brake power. However, as the load surpassed 6 kg, the biodiesel blends (B2.5, B5, and B10) exhibited elevated brake power. Specifically, B2.5, B5, and B10 showcased 2.74 %, 3.13 %, and 6.76 % higher brake power, respectively, relative to diesel fuel. The increase in brake power can be attributed to a higher oxygen content in biodiesel, facilitating more complete combustion and subsequently improved brake power due to enhanced mass flow. The presence of propanol in the blends further contributed to this effect, aligning with previous reports that propanol can enhance brake power in biodiesel blends [67].

Interestingly, the relationship between BP and biodiesel volume revealed a distinctive pattern. BP increased proportionally with increase in biodiesel volume until a 10 % blend, after which it began to decrease with higher biodiesel content in the blend. This trend reflects the complex interplay between fuel properties and combustion dynamics in different blend ratios suggesting an optimum blend ratio of 10 %. At maximum load, the BP of B20 was marginally lower than that of diesel fuel by 1.22 %. This finding is in line with similar trends reported by Imdadul et al. [68], where B20 biodiesel from a Jatropha/diesel/pentanol blend exhibited a slightly lower brake power by 1.29 %. Such minor deviations in BP indicate the possibility of utilizing higher biodiesel blend ratios beyong 10 % in diesel engines without the necessity of any modifictions.

3.3. *Emission composition analysis*

Exhaust gas emissions of the fuels are discussed in this section. The exhaust emissions of biodiesel fuel have been reported to depend on the cetane number of the fuel, fatty acid composition, length of the carbon chain (C/H ratio), density and viscosity [15,16,69,70].

3.3.1. *Carbon monoxide (CO) emissions*

CO emissions indicate the unburnt fuel that occurs from incomplete combustion due to a low air-fuel ratio in the combustion chamber, insufficient combustion period and poor fuel properties [22]. Fig. 9 illustrates the variations in CO emissions of biodiesel and biodiesel blends with engine load compared to diesel fuel.

The investigation CO emissions from BSFL biodiesel yielded insightful observations. Initially, the CO emissions decreased as engine load increased, reaching a minimum level (0.09–0.1 %) at a 6 kg load kg and then increase with a further increase in load, as illustrated in Fig. 9a. The observed trend could be attributed to the attainment of maximum thermal efficiency at a 6 kg load, suggesting an optimal operational load point. Biodiesel displayed lower CO emissions in comparison to diesel fuel, signifying more complete combustion characteristics for the former.

The analysis of CO emissions reduction revealed consistent trends across the biodiesel samples. The average decrease in CO emissions for B100 compared to diesel was 24.71 %, 24.08 % and 22.06 % for NaOH/CA, CaO/CA, and CaO-synthesized biodiesel, respectively. An increase in diesel composition in the fuel blend resulted in decreased oxygen content and subsequently led to increased CO emissions as depicted in Fig. 9b. For all samples examined, the CO emissions were within the recommended limits for

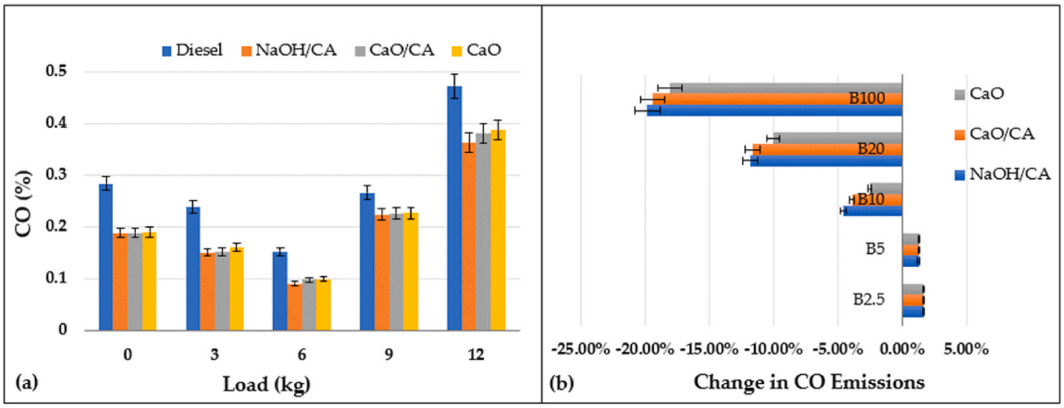

Fig. 9. CO emissions characteristics: (a) Biodiesel produced by different catalysts and diesel versus engine load (b) percentage changes in CO emissions for biodiesel and blends concerning diesel fuel at 12 kg load.

light and heavy duty vehicles, as well as clean screen programs, that recommend maximum CO emissions of 0.5 % [71].

Furthermore, examining the impact of biodiesel blends on CO emissions unveiled interesting results. As anticipated, B2.5 demonstrated the lowest reduction in CO emissions (3.35–3.53 %), while B100 exhibited the highest decrease, indicating superior combustion characteristics for BSFL biodiesel. Strikingly, even in the presence of 10 % propanol, lower BSFL biodiesel blends (B2.5, B5 and B10) demonstrated lower CO emissions compared to diesel. This finding contrasts some earlier research suggesting that higher alcohols might elevate CO emissions. Nevertheless, Kadir et al. [22] reported noteworthy CO emission reductions of 11.57 % for B20 safflower biodiesel/diesel blend (70 %)/pentanol (10 %) compared to diesel. They further noted that increasing pentanol to 20 % lowered CO emissions by 31.61 %. The reduced CO emissions could be attributed, in part, to the low unsaturation characteristic of BSFL biodiesel. As previously discussed, BSFL biodiesel is highly saturated. These results agree with studies by Knothe et al. [63] and Jambulingam et al. [69] which demonstrated that CO emissions increased with the degree of unsaturated fatty acids.

The influence of catalyst synthesis with CA displayed mixed effects across different biodiesel blends. The impact was less evident in B2.5, B5, and B10, potentially due to the dominant presence of propanol and diesel in the blends. Conversely, B20 and B100 demonstrated a more pronounced effect, likely attributable to higher biodiesel content. Specifically, CO emissions for B20 decreased by 20.95 %, 20.64 %, and 18.06 % for biodiesel produced by NaOH/CA, CaO/CA, and CaO, respectively, relative to diesel fuel.

3.3.2. Carbon dioxide (CO_2) emissions

CO_2 is an important parameter for consideration as it directly contributes to an increase in Green House Gases (GHG) emissions. However, CO_2 emissions are mostly not considered in biodiesel combustion since biodiesel production, which depends on the feedstock type and source, is considered to have a negative or neutral carbon balance [72–76]. The variations in CO_2 emissions with engine load of biodiesel and the percentage reduction compared to diesel are presented in Fig. 10.

The examination of CO_2 emissions unveiled a clear relationship with both engine loading and the diesel volume percentage in the blend. It's evident that CO_2 emissions intensified with increased engine loading and diesel volume percentage in the blend. Notably, the CO_2 emissions from diesel fuel surpassed those from biodiesel and the blends across all tested loads. However, biodiesel CO_2 emissions has been subject to conflicting reports within the literature. Some studies have suggested an increase in emissions due to the high oxygen content of biodiesel [22,34] while others have reported contrasting outcomes, attributing them to the lower carbon-to-hydrogen ratio of biodiesel [77]. Furthermore, biodiesel CO_2 emissions are known to be influenced by the feedstock type and the degree of saturation of the present fatty acids [19,26,69,78]. An experiment by Abed et al. [26] demonstrated that while biodiesel derived from Jatropha, palm oil, and algae exhibited lower CO_2 emissions than diesel fuel, biodiesel from waste cooking oil displayed increased CO_2 emissions.

A broader perspective emerges from life cycle assessments of biodiesel, revealing substantial reductions in overall greenhouse gas (GHG) emissions. For biodiesel from oil crops, these reductions ranged from 40 % to 69 %, whereas biodiesel from sources like tallow oil, distillers, corn oil, and waste cooking oil exhibited even higher reductions, ranging from 79 % to 86 % [79].

The analysis of CO2 emissions for various biodiesel samples yielded intriguing results. B100 displayed the most significant reduction in CO2 emissions, by 43.74, 41.71 and 37.91 % for biodiesel synthesized by NaOH/CA, CaO/CA and CaO, respectively, at maximum load (Fig. 10a). The lower CO_2 emissions in BSFL biodiesel can be attributed to its low composition of unsaturated fatty acids. These findings agree with a study by Jambulingam et al. [69], wherein long-chained fatty acids were associated with increased CO_2 emissions in biodiesel. Another study by Allami & Nayebzadeh [36] similarly reported that unsaturated fatty acid composition correlated with elevated CO_2 emissions in biodiesel.

The effect of synthesizing catalysts with CA on CO_2 emissions was evident in B10, B20 and B100 due to their high biodiesel content (Fig. 10b). Overall, NaOH/CA and CaO/CA biodiesel exhibited reduced CO2 emissions by an average of 3.81 % and 1.21 %, respectively, when compared to CaO-synthesized biodiesel. The elevated CO2 emissions associated with CaO catalysts could be attributed to the presence of absorbed CO2, necessitating substantial activation energy for removal [80].

3.3.3. Hydrocarbons (HC) emissions

HC emissions result from unburnt fuel due low oxygen-fuel ratio in the combustion chamber. Biodiesel from BSFL and its blends was found to have very low HC emissions compared to diesel fuel, as illustrated by Fig. 11.

The investigation into hydrocarbon (HC) emissions yielded consistent results, where emissions increased with engine load. This finding agrees with previous experimental studies conducted by Kadir et al. [22] and Abed et al. [26]. The maximum HC emissions allowable for light and heavy vehicles is 200 ppm indicating that the HC emissions for all fuel samples were withing the recommended limit [71]. This signifies compliance with emission standards across the board.

Comparing HC emissions reduction between neat biodiesel (B100) and diesel fuel, a clear trend emerged. The average reduction in HC emissions from B100 compared to diesel fuel was 53.01 %, 52.62 % and 50.19 % for biodiesel catalyzed with NaOH/CA, CaO/CA and CaO, respectively (Fig. 11a). Notably, at maximum load, the reduction in HC emissions for pure biodiesel was even more pronounced, reaching 92.01 %, 89.03 % and 83.17 % for biodiesel catalyzed with NaOH/CA, CaO/CA and CaO, respectively. This aligns with a study by Yesilyurt et al. [31], who reported an 86.65 % reduction in HC emissions due to the use of biodiesel, highlighting the potent potential of biodiesel in reducing HC emissions.

The impact of synthesizing catalysts with CA on HC emissions was noticeable. B100 produced by NaOH/CA and CaO/CA exhibited an average HC reduction of 5.83 % and 4.95 %, respectively, compared to CaO catalyst. These results suggest that synthesizing the catalysts with CA improved the oxygen content in biodiesel, consequently resulting in lower HC emissions. Previous studies have also reported the contribution of fatty acid composition to HC emissions, with biodiesel derived from waste fish fat and chicken fat showing respective reductions of 12.31 % and 14.84 % in HC emissions [17].

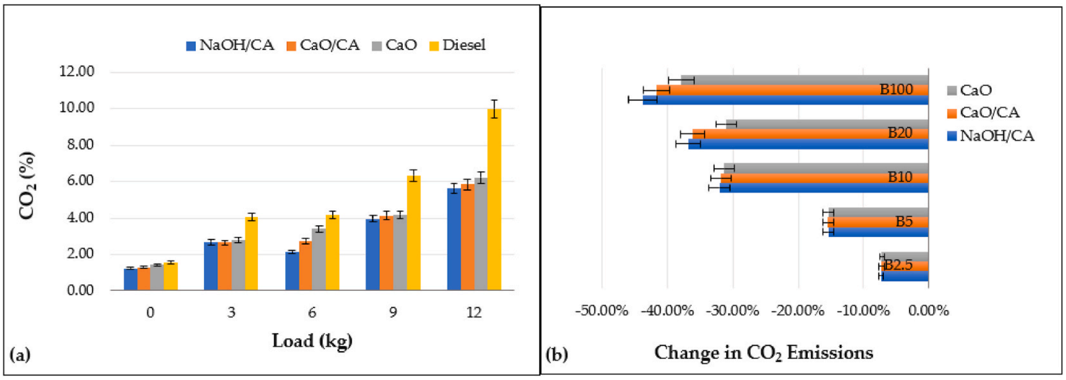

Fig. 10. CO_2 emissions (a) biodiesel produced by different catalysts and diesel versus engine load (b) percentage CO_2 reduction in biodiesel and blends regarding diesel fuel at maximum load.

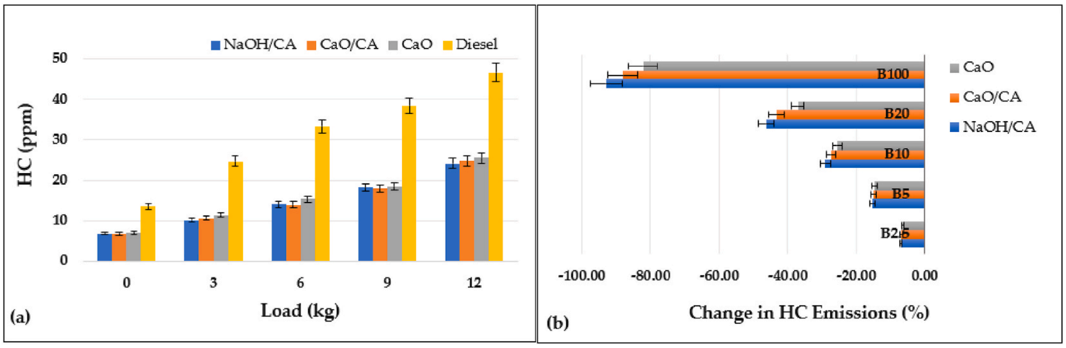

Fig. 11. HC emissions results (a) biodiesel produced by different catalysts and diesel versus engine load (b) percentage HC reduction in biodiesel and blends concerning diesel fuel at maximum load.

The substantial reduction in HC emissions observed in this study can be attributed to the high concentration of saturated fatty acids in BSFL biodiesel, as previously discussed in Section 3.1. Such biodiesel composition is known to possess high oxygen content and low HC emissions [15,16,70]. Furthermore, the relationship between HC reduction and increasing biodiesel content in blends was evident Fig. 11b. Overall, all blends demonstrated HC reduction, emphasizing the positive impact of even small volumes of BSFL biodiesel in the blends, such as B2.5 (6.31–6.37 %) and B5(14.76–15.29 %). These results show the efficacy of BSFL biodiesel in improving the air/fuel ratio of diesel fuel and subsequently enhancing combustion efficiency. These results agree with findings by Xue et al. [19], who reported that increased saturation concentration of biodiesel corresponded to lower HC emissions.

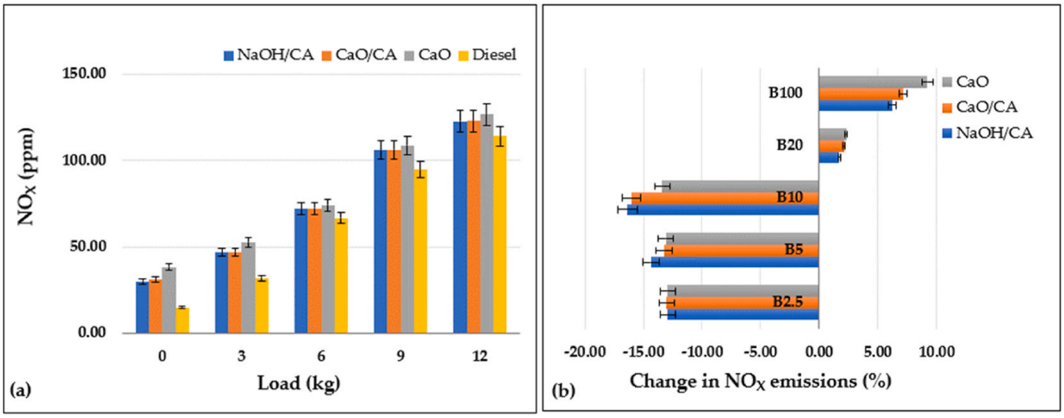

Fig. 12. NO_X Emissions Results (a) Biodiesel Produced by Different Catalysts and Diesel Versus Engine Load (b) Percentage Change in NO_X emissions in Biodiesel and Blends Regarding Diesel Fuel at Maximum Load.

3.3.4. Oxides of nitrogen (NO_X) emissions

NO_X emissions in biodiesel combustion occur due to the supply of enough oxygen resulting in increased combustion temperatures and complete combustion of the fuel. Air contains 78 % of nitrogen which react with oxygen in the reaction chamber to form nitrogen oxides. Other factors contributing to increased NO_X emissions in biodiesel include higher cetane number, viscosity and iodine number [31]. Biodiesels have increased NO_X emissions compared to diesel fuel, contributing to one of the challenges in the development of biodiesel [81]. The variations in NO_X emissions with engine load for neat BSFL biodiesel and the percentage change in emissions when compared to diesel fuel are presented in Fig. 12.

The investigation into NO_X emissions revealed a clear correlation with engine load, as emissions increased from 30.20 to 38.22 ppm at 0 kg load and escalated to 122.82–126.8 ppm at 12 kg load. indicating engine's response to changing load conditions. Neat biodiesel (B100) exhibited higher NO_X emissions compared to diesel fuel across all loads as depicted in Fig. 12a. These findings are consistent with an experimental study by Rehman et al. [32] which pointed out that BSFL biodiesel produced higher NO_X emissions compared to diesel due to higher oxygen content resulting in prolonged combustion period. It's worth to mention that the recorded NO_X emissions for all fuel samples were well below the maximum allowable limit of 1000 ppm for light and heavy vehicles [71], ensuring compliance with clean screen vehicle regulations.

Interestingly, the magnitude of emissions changes was more pronounced at lower loads (below 6 kg) compared to higher engine loads, potentially attributed to high BSFC at 0 kg load. At maximum load, B100 exhibited changes in NO_X emissions of 6.26 %, 7.15 %, and 9.22 % for biodiesel catalyzed with NaOH/CA, CaO/CA, and CaO, respectively, compared to diesel fuel. Catalysts synthesized with CA demonstrated their effectiveness in reducing NO_X emissions in B100 by 3.16 % (NaOH/CA) and 2.23 % (CaO/CA) at maximum load.

The variation in NO_X emissions has been extensively reported to depend on type of feedstock, which dictates the fatty acid composition of the biodiesel [25,78]. Many studies have reported higher NO_X emissions (exceeding 10 %) from vegetable oil-based biodiesel [82,83]. Results shows that the NO_X emissions from BSFL range between 6.26 % and 9.22 % reflecting lower emissions compared to biodiesel derived from vegetable oils but higher than those of diesel fuel. A study by Kamurlzaman et al. [7] further corroborates this pattern by demonstrating lower NO_X emissions from BSFL biodiesel in comparison to diesel fuel. This behavior indicates the potential of BSFL biodiesel, sourced from waste, un minimizing NO_X emissions compared to biodiesel from vegetable oils.

Blending biodiesel with diesel and propanol reduced NO_X emissions by 15.49 % in B10. However, further addition of biodiesel content beyond 10 % increased NO_X emissions (Fig. 12b). These results suggest that B10 offers the most favorable blend ratio for minimizing NO_X emissions, achieving a notable reduction of 16.36–13.38 % compared to diesel fuel. Overall, B10 (NaOH/CA) emerged as the optimal blend ratio for curtailing NO_X emissions.

The reduction in NO_X emissions in lower blends (B2.5, B5 and B10) can be attributed to improved viscosity in the fuel blend, high saturation of BSFL biodiesel and balanced air-fuel ratio. Biodiesel with a high composition of unsaturated fatty acids has been associated with increase NO_X emissions, while saturated fatty acids tend to reduce NO_X emissions [15,63,69]. Besides, CA-based catalysts have been linked to have improved particle dispersion, surface area and porous sites, effectively acting as NO traps resulting in reduced NO_X emissions [84–86]. The findings from this study affirm that catalysts synthesized with CA hold the potential to minimize NO_X emissions from CI engines.

3.3.5. Smoke opacity

Smoke is the undesirable end product of fuel combustion, which indicates the state of an incomplete combustion process in CI engines [22]. The variations in exhaust smoke opacity with engine load for biodiesel and biodiesel blends in this study is presented in Fig. 13.

The investigation into smoke opacity revealed a consistent pattern, where opacity increased with engine load across all fuel samples. As expected, diesel fuel exhibited high smoke emissions for all tested engine loads, as presented in Fig. 13a. Biodiesel has high

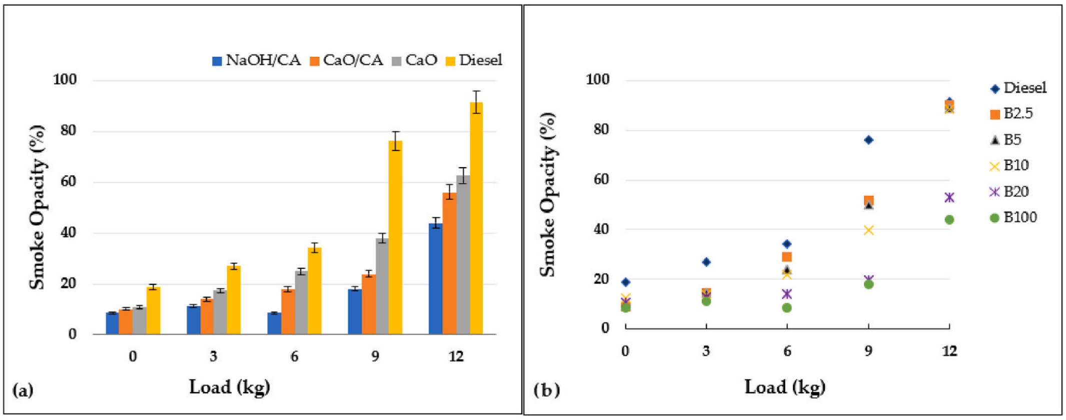

Fig. 13. Smoke opacity variation with engine load for (a) BSFL biodiesel produced using different catalysts and diesel (b) biodiesel, biodiesel blends and diesel.

oxygen content (11 %), which contributes to improved fuel combustion resulting in lower soot emissions, compared to diesel fuel [22]. On average, the biodiesel demonstrated remarkable reductions in smoke opacity by 63.47 %, 50.65 % and 37.92 % for biodiesel synthesized using NaOH/CA, CaO/CA and CaO catalysts, respectively.

The low smoke emissions from biodiesel indicate that biodiesel from BSFL has a high oxygen concentration, which promotes combustion. Besides, the composition of saturated fatty acids in BSFL biodiesel contributes significantly to this outcome, as they have been reported to reduce particle matter by 82–83 %, surpassing the 73 % reduction associated with unsaturated fatty acids [63]. Biodiesel produced by catalysts synthesized with CA exhibited even lower smoke opacity by 41.15 % (NaOH/CA) and 20.51 % (CaO/CA) compared to commercial CaO catalysts. This aligns with previous research demonstrating that CA-assisted sol-gel catalysts enhance soot oxidation, leading to improved emissions performance [84,87]. These results strongly indicate the effectiveness of catalyst synthesis with CA in curbing smoke emissions in biodiesel.

The smoke opacity increased with a decrease in biodiesel content in the blend, as seen in Fig. 13b. The smoke emissions were lower by 1.53 %, 2.84 %, 3.27 %, 42.07 % and 51.91 % in B2.5, B5, B10, B20 and B100, respectively, when compared to diesel fuel at maximum load. Comparable findings have been reported in the literature, with neat rapeseed biodiesel reducing smoke emissions by 50 % [83], and Jatropha biodiesel (B20) demonstrating a reduction of 13.7–24.48 % compared to traditional biodiesel [68]. The ability of lower biodiesel blends (B2.5, B5 and B10) to reduce smoke emissions indicates the significant potential of BSFL biodiesel to substantially alleviate emissions in CI engines.

4. Conclusion

The performance and emission characteristics of BSFL biodiesel on IC engine were used to evaluate the effectiveness of transesterification catalysts synthesized with CA on biodiesel quality. The findings provide valuable insights into the potential of enhancing biodiesel quality through catalyst synthesis.

In terms of engine brake power, B100 exhibited a marginal reduction compared to diesel fuel, ranging from 4.21 % to 7.83 %. However, the introduction of CA-based catalysts led to noteworthy improvements. Specifically, the brake power of the biodiesel was enhanced by 3.47 % (NaOH/CA) and 2.61 % (CaO/CA) when compared to biodiesel produced using commercial CaO catalysts.

Except for NO_X emissions, all other exhaust gas emissions from neat biodiesel were lower than those of diesel fuel. The reduction in exhaust emissions can be attributed to a high cetane number and high SFA composition (72.86–73.06 %) of BSFL biodiesel. The NO_X emissions from biodiesel increased by 6.26–9.22 % compared to diesel fuel. Synthesizing catalysts with CA effectively reduced NO_X, HC and Smoke opacity by 3.16 %, 5.83 % and 41.15 % for NaOH/CA and 2.23 %, 4.95 % and 20.51 % for CaO/CA, respectively, compared to biodiesel from CaO catalyst.

The optimal blend ratio emerged as B10, consisting of 10 % biodiesel, 10 % propanol, and 80 % diesel. B10 showcased improved engine performance and reduced emission levels compared to diesel fuel. This finding suggests B10's potential in curbing GHG emissions in diesel engine applications, indicating its viability for practical implementation.

In summation, synthesizing catalysts with CA enhanced both engine performance and emission characteristics of BSFL biodiesel. As a recommendation for future research, an exploration into the effects of blending BSFL biodiesel with biodiesel rich in unsaturated fatty acids could shed light on its implications for engine performance and emissions.

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Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Lilies K. Kathumbi: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition, Project administration, Resources. **Patrick G. Home:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing. **James M. Raude:** Conceptualization, Data curation, Project administration, Supervision, Writing – review & editing. **Benson B. Gathitu:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing 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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