Renewable Energy 215 (2023) 119008

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Energy outputs and emissions of biodiesels as a function of coolant temperature and composition

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ARTICLE INFO

Keywords:
Biodiesel
Coolant temperature
Ester composition
Emission
Performance
Waste

ABSTRACT

Strict emission legislation forced engine manufacturers to replace fossil diesel with sustainable biofuels. Biodiesel combustion produced lower thermal efficiency and higher nitric oxide (NO) emissions. The NO gas emissions depend on the saturated fatty acid (SFA) and unsaturated fatty acid (USFA) levels present in the plant oil. To overcome biodiesel combustion challenges, effective utilisation of engine waste heat could help in achieving high thermal efficiency and low emissions. Effects of biodiesel SFA and USFA levels, and engine coolant temperature on four different biodiesel types are studied. Lamb fat biodiesel (LFB), chicken fat biodiesel (CFB), waste cooking oil biodiesel (WCOB), and Karanja biodiesel (KB) were used. LFB and CFB have higher SFA%, whereas WCOB and KB have higher USFA%. The coolant temperature was varied from 65 °C to 85 °C at different engine loads. It was observed that with increased coolant temperatures, the brake thermal efficiency of the engine was increased by 4–5% with LFB and CFB compared to diesel, due to reduced heat losses and better oxy-fuel combustion. The NO and CO_2 emissions for high SFA fuel (LFB and CFB) were reduced by 19–22% and 0.2–6%, respectively, as compared to USFA rich fuel (WCOB and KB) and diesel fuel. However, smoke emissions were found to be higher for CFB, WCOB, and KB than diesel, but LFB produced 4–6% less smoke than USFA (WCOB and KB) and diesel fuel. The study concludes that coolant temperature influences engine performance and pollutants, but use of appropriate SFA-level biodiesel could reduce emissions without compromising thermal efficiency.

1. Introduction

Global concerns about the price of crude oil and the state of the atmospheric pollution have led scientists to search for alternative energy sources [1]. The shift to sustainable alternative fuels for mobility is necessary since this sector consume huge quantity of fossil fuels [1]. Numerous studies suggest that biodiesel can effectively replace diesel fuel in compression ignition (CI) engines [2]. In comparison to fossil diesel, biodiesel offers several benefits: first, it is a sustainable clean energy source; second, the amount of carbon dioxide (CO_2) that is absorbed by the plants during the growing process significantly reduces the environmental impact [1]; and third, certain pollutants, such as smoke, soot, and particulate matter (PM) are typically lower as compared to fossil fuel [2,3]. The biggest drawback is the need for new fuel systems that adhere to the unique characteristics of biofuels. In addition, researchers reported a rise in nitrogen oxides (NOx) emissions when biodiesel was used instead of fossil diesel [3].

To limit exhaust emissions from diesel engines, different rules have been implemented in industrialised nations. Manufacturers of vehicles and engines place this as a high priority R & D activity to reduce engine out pollutants [2]. Engines research community throughout the world are extremely interested in finding renewable alternatives to reduce engine out pollution [3]. To meet the challenges of environment and resources, the manufacturers, and experts must look for a new renewable energy and advancement of the technologies [4]. Many different techniques are being investigated to achieve lower engine out emissions. They can be divided into three categories; (a) improved engine design, (b) higher engine combustion efficiency, and (c) lower fuel consumption [1]. In addition, exhaust gas treatment with catalytic converters or diesel filters is used to reduce pollutants in the exhaust gas [1,4].

The cooling system in CI engines ensures that the engine construction

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https://doi.org/10.1016/j.renene.2023.119008
Received 16 January 2023; Received in revised form 2 July 2023; Accepted 8 July 2023
Available online 8 July 2023

Nomenclature

AV	Acid value
BSFC	Brake specific fuel consumption
BT	Butanol
BTE	Brake thermal efficiency
bTDC	Before top dead centre
CI	Compression ignition
CO_2	Carbon dioxide
CO	Carbon monoxide
CFB	Chicken fat biodiesel
CN	Cetane number
EGT	Exhaust gas temperature
FA	Fatty acids
FAME	Fatty acids methyl esters
HHV	Higher heating value
HC	Hydrocarbon
IDICI	Indirect injection compression ignition
IMEP	Indicated mean effective pressure
JO	Jatropha oil
KB	Karanja biodiesel
LFB	Lamb fat biodiesel
MUSFA	Mono-unsaturated fatty acids
NOx	Nitric oxides
PM	Particulate matter
PUSFA	Poly unsaturated fatty acids
SFA	Saturated fatty acids
WCO	Waste cooking oil
WCOB	Waste cooking oil biodiesel

remains thermally sound. Therefore, the cooling system has a direct impact on the temperature of combustion within the engine [5]. Hossain et al. [6] investigated the performance and emissions analysis of diesel engine fuelled with neat jatropha oil (JO) and butanol (BT) blend by varying the engine coolant temperature from 50 to 90 °*C*. They reported up to 31% reduction in carbon monoxide (CO) emissions at 80% engine load when coolant temperature was increased from 60 °C to 90 °*C*. The JO blend showed 10% lower NOx emissions as compared to fossil diesel at 80% load and at 90 °*C* coolant temperature. They also reported that thermal efficiency of biofuel was found to be slightly higher and brake specific fuel consumption (BSFC) was reduced with rise in coolant temperature [6]. He et al. [7] examined the effect of coolant temperatures (45, 60, 75 & 90 °*C*) on stratified-charge direct-injection spark-ignition engine with E30 blend (30% ethanol in gasoline). They reported that engine performance was improved at higher temperature of 90 °*C* . Increased values of in-cylinder temperature, bulk gas temperature and indicated mean effective pressure (IMEP) were observed. At 90 °*C* and constant injection timing, combustion duration was found to be shorter, and crank angle (CA) position CA10, CA50 and CApm90 were advanced due to better combustion efficiency. The CO, hydrocarbon (HC) and PM emissions were reduced but NOx gas emission was increased. The optical analysis showed shorter ID periods and slow fuel vaporisation rate at lower temperature, which reduced the duration of pre-mixed combustion and prolonged the diffusion combustion phase. At low coolant temperature, the area of diffusion combustion phase was found to be 4 time higher than 90 °*C* coolant temperature [7].

Another study on coolant temperature was examined by Song et al. [8] on gasoline direct injection (GDI) engine by varying injection timing and injection pressure. They fixed the operating parameter of GDI engine such as coolant temperatures of 40 °*C* and 80 °*C*, injection timing of 360-210 ° bTDC (before top dead centre), and injection pressure range of 5–50 MPa. The authors reported that at wall wetting condition (330° bTDC) and injection pressure range of 10–50 MPa, particulate number (PN) emission was decreased by 90%. Furthermore, HC was found to be lower by 30% with 10% changes in injection timing and pressure [8]. An advanced study on engine coolant temperature was reported by Luo et al. [9] using 2.3L turbocharged hydrogen engine. They reported that the brake thermal efficiency (BTE) was improved by about 3.69% and 7.67% at 2000 rpm and 4000 rpm respectively at different loads and equivalence ratio ranges of 0.4–0.9. They found out that the effects of changes in coolant temperature on speed are small, and BTE was changed by up to 0.7% in all operating conditions. This study suggest that rise in cooling temperature and engine load improved BTE. Ma et al. [10], investigated engine coolant temperatures and n-butanol as additive on the combustion and emission performance of a Euro-VI heavy-duty diesel engine. They found that with increasing load, under idle and high-speed conditions, the maximum in-cylinder pressure (Pmax) was retarded. When the coolant temperature was increased to 100 °*C*, BSFC was decreased. Higher coolant temperature reduces fuel consumption and as a result, improves the Soot-NOx trade-off [10]. Singh et al. [11] studied the impact of waste heat recovery at higher coolant temperature using of Volvo 4-cylinder light duty diesel engine. At different operating conditions, the coolant temperature was varied from 80 to 160 °*C*. They found out that up to 1% increment in brake thermal efficiency due to lower heat losses, whereas NOx emission was increased by up to 0.9 g/kWh because of higher in-cylinder temperature [11].

The temperature of the lubrication oil and exhaust gas recirculation (EGR) are also affected by the cooling system, which influences the engine performance characteristics [12]. Low coolant temperatures will lead to enhance the heat transmission and reduce temperatures in the cylinder head, cylinder, and piston [13]. The lower level of average gas temperature and pressure will lead to increased frictional losses. This will then lower the work per cycle supplied to the piston [13]. Additionally, thermal stresses produced by temperature gradients are increased when coolant temperatures are lower. Variations in gas temperature induced by changes in coolant temperature affect the production of NOx, CO, CO_2, and HC gases [14]. These emissions are the most important greenhouse gases (GHG) causing global warming effects. These harmful emissions can be controlled by using high quality biofuels, advanced after gas treatment technology and optimised engine operating conditions. Biofuels are carbon neutral due to renewables in nature and able to reduce CO_2 gases from the atmosphere in their life cycle [15].

Biodiesel can be made from locally available feedstocks, is a renewable source of energy [16]. The biodiesel fuel is a combination of fatty acid alkyl esters derived from vegetable oils, animal fats, and recycled greases [17]. Neat biodiesel (B100) can be used in diesel engines with little or no modifications to the engine. Biodiesel is easy to use, sustainable, nontoxic, and almost sulphur free. It's often used as a petroleum diesel addition to help diesel-powered cars emit less particles, carbon monoxide, hydrocarbons, and toxics [18]. The change in fatty acid (FA) composition depending on the carbon chain length and degree of saturation level of the esters, governs several aspects of biodiesel fuel quality. The fatty acid methyl ester (FAME) profile of biodiesel differs significantly depending on the origin of the oils or fats [19]. The FA composition influences properties such as cetane number, kinematic viscosity, density, oxidative stability, and cloud point. Saturated fatty acids (SFA) include single carbon-carbon (C-C) bonds, while unsaturated fatty acids (USFA) contains double carbon = carbon (C=C) bonds [20]. Mono-unsaturated fatty acids (MUSFA) have just one (C=C) double bond, while poly-unsaturated fatty acids (PUSFA) have more than two double bonds in their FA chain. The carbon chain length, presence of double bonds (C=C), position and geometric configuration (cis or trans) of the double bonds, and the presence of additional functional groups influences the physical and chemical properties of a fatty acid alkyl ester molecule [21].

Except for NOx emissions, biodiesel produced less emissions than diesel [22]. NOx gas emissions increase with the increase in the number of double bonds in biodiesel. Double bonds (C=C) raises the adiabatic flame temperature during the combustion process, Rise in the global in-cylinder temperature will lead to rise in the thermal NOx [22]. Researchers have studied the effects of single fatty acid molecules on combustion and emission properties. Saturated fatty acids produce less NOx than unsaturated fatty acids [23]. The combustion process is quicker for SFA molecules due to their better fuel properties such as lower density and viscosity values, and higher cetane number. This will then lead to decreased ignition time, which would lower the formation of thermal NOx [23]. The molecular structure of the feedstock oil and different kinds of fatty acids present in the FAME profile effects biodiesel fuel quality. Biodiesel fuel properties effects engine combustion, performance, and emissions characteristics. Moreover, engine operating condition also have great impact on engine combustion and emissions characteristics. Engine jacket water-cooling temperature can be controlled through water flow rate valve, which leads to increase or decrease the engine cylinder and cylinder head metal temperature. This water-cooling temperature directly effects the engine performance and emissions characteristics. Researchers have investigated use of different types of neat biodiesels and biodiesel blends; such as biodiesel-diesel blends, blends with different alcohols and additives in engines [24–27]. These studies were focused mainly by varying engine loads, speed, injection pressure, dual-fuel combustion mode etc. A limited number of studies are available investigating the effects of engine coolant temperature on single neat biodiesel and biodiesel-diesel/alcohol blends [6–15]. Whereas a comparison study on engine coolant temperature on different types of neat biodiesels based on their molecular structures such as higher saturation and unsaturation level has not been investigated yet. In this study, waste cooking oil biodiesel (WCOB), waste animal fat (lamb & chicken) biodiesel and non-edible oil (karanja) biodiesel are investigated on a two-cylinder water cooled diesel engine at different coolant temperatures (65 and 85 °C) and constant speed of 2500 rpm under full load (23.5 Nm) and part-load (18.5 Nm) conditions. Consequently, an attempt has been made to understand the corelation between biodiesel fatty acids compositions (saturation and unsaturation level) and engine cooling temperature. The main objectives of this study are: (a) to develop a correlation of biodiesel fuel saturated and unsaturated fatty acids levels with coolant temperatures, and (b) effect of coolant temperature on engine performance and exhaust emissions with different neat biodiesels at the same engine. This study would provide a broad knowledge to the researchers to understand the importance of balancing the biodiesel fatty acids before selecting to be used as fuel for off-road and mobile applications in diesel engine.

2. Materials and methods

Four different oil feedstocks such as waste cooking oil, waste animal fats (lamb and chicken) and Karanja oil were selected for this experimental study based on the availability in the local market (Birmingham, UK). For biodiesel production, Sulphuric acid (H_2SO_4), Potassium hydroxide (KOH) and Methanol (CH_3OH) were purchased from Fisher Scientific (UK). WCO was collected from the University Cafeteria and animal fats were collected from local market.

2.1. Biodiesel production

Waste animal fat (lamb and chicken) was rinsed with distilled water to remove residuals. To increase the yield of fat, large chunks were sliced into little pieces, cooked for 1 h at 100 °C to melt the fat (Fig. 1). The melted fat was separated through the filter to eliminate insoluble impurities. and stored in an airtight bottle. Acid value (AV) of the parent oil was measured before starting the biodiesel production. The AV data denoted which steps should be taken such as either 2-step (esterification) or 1-step (transesterification) process for biodiesel production. The AV can be calculated using Eq. (1), where Vt-titration volume (ml), 0.1N- normality of the titrant (KOH) and Mw-molecular weight of the titrant used (KOH) in g/mol [28]. Karanja oil is a non-edible oil with a high acid value; hence two-step process is required. To lower the acid value, an acid catalysis procedure (esterification) was applied. In this case, methanol-to-oil molar ratio (6:1M) was utilised, with 2% (v/v) sulphuric acid (H_2SO_4) added to the warmed oil at 60 °C . The mixture was then swirled for 3 h at 600 rpm with a continuous stirrer speed. After the reaction, the liquid was transferred to a separating flask and allowed to settle overnight to separate the esterified oil from the top layer. The esterified oil was then heated to 60 °C under vacuum for 1h to eject the methanol and water [19].

The base-catalyst (transesterification) technique was utilised to

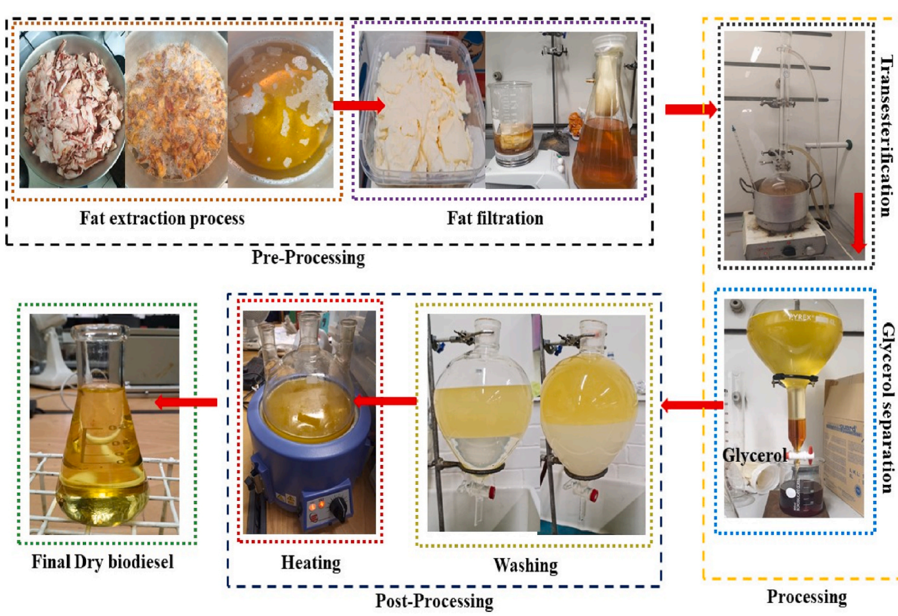

Fig. 1. Biodiesel production from waste resources.

manufacture biodiesel from lamb fat, chicken fat, and esterified Karanja oil. A methanol to oil molar ratio (4:1) and 1% (wt./wt.) base-catalyst (KOH) was used in the transesterification process. As illustrated in Fig. 1, methanol and KOH solution was prepared and added to the warmed oil at 65 °C, then agitated for 90 min at 600 rpm using a magnetic stirrer [19]. The mixture was then transferred to a separating flask and allowed to settle overnight to separate the glycerol from the methyl ester. To remove the catalyst and soap that generated during the transesterification process, raw biodiesel was carefully separated and washed with hot (80–85 °C) de-ionised water [19] (Fig. 1). After that, the washed biodiesel was dried at 110 °C with nitrogen flushing (Fig. 1). The yield % of the final product was calculated using Eq. (2) [28].

$$\text{Acid value (mgKOH / g)} = \frac{V_t \times 0.1N \times Mw}{Oil\ sample\ weight} \tag{1}$$

$$\text{Biodiesel yield (\%)} = \frac{Weight\ of\ biodiesel\ produced\ (g)}{Oil\ sample\ weight\ (g)} \times 100 \tag{2}$$

2.2. Engine experimental setup & measurements

The engine tests were carried out on a 2-cylinder non-road water-cooled indirect injection compression ignition (IDICI) engine (Fig. 2). Table 1 shows specification of the engine. A GUNT CT-300 on-line performance software was used to analyse the combustion and performance. The engine was tested at a constant speed of 2500 rpm under full load (23.5 Nm) and part-load (18.5 Nm) conditions, with engine coolant temperatures of 65 °C and 85 °C. The engine coolant temperature was maintained by controlling the water flow rate along with a rotameter. The control panel recorded performance characteristics such as rotational speed, torque, air intake flow rate (litres/min), intake air temperature (°C), exhaust gas temperature (°C), coolant water temperatures (inlet and outlet) (°C), oil temperature (°C), and fuel consumption duration for a certain volume of fuel. Bosch BEA 950 gas analyser was used to measure exhaust gas emissions and the details of the instrument are listed in Table 2.

3. Results and discussions

The findings of the investigations have been discussed in two-parts: (i) physical and chemical properties of biodiesels used in this study (2) engine performance and emissions parameters.

3.1. Biodiesel fuel properties analysis

Fuel samples were analysed in the fuel laboratory internally by using a variety of analytical instruments. Fatty acid compositions of the test fuels were carefully reviewed through the literatures and mentioned in Table 3. The fatty acids methyl ester compositions are calculated using Equations (3)–(5) [29]. It was observed that LFB and CFB consists of higher amount of saturated fatty acids about 34.46% and 27.94% respectively (Fig. 3). The LFB was found rich in SFA which mainly consists of C16:0 (21.1%) and C18:0 (11.16%). Higher mono-unsaturated (MUSFA) was found in KB about 54.71%, whereas higher poly-unsaturated (PUSFA) was observed in CFB about 32.9%. All measurements were repeated three times, with an average value derived that was confirmed to be within the biodiesel standard limits (Table 4). Cetane number (CN) is directly dependent on the SFA%, higher the SFA higher the cetane number [30]. LFB and CFB shows the higher CN about 59 and 57 respectively (Table 4). Higher heating value (HHV) were observed for CFB and KB about 40.43 MJ/kg and 40.87 MJ/kg, it is mainly due to higher content of PUSFA %. Higher number of double bonds reduced the overall oxygen % and improved the heating value (C/H %) [30].

$$\text{SFA \%} = \sum (C-C)\ single\ bond\ in\ FAs \tag{3}$$

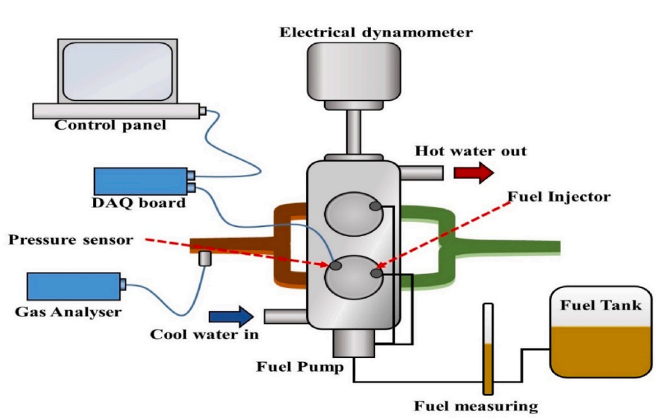

Fig. 2. Experimental test rig.

Table 1
Specification of the test engine.

Manufacturer	Yanmar
Model	2TNV70
No. of cylinders	2
Type of injection	Indirect
Cooling system	Liquid cooled
Bore × Stroke	70 × 74 [mm]
Displacement	0.570 [L]
Rated output power	7.5 kW at 2,500 rpm

Table 2
Exhaust emission analyser specifications.

Exhaust gas measuring module		
Designation	Measuring range	Resolution
CO	o-100% vol.	0.001% vol.
CO2	0–18% vol.	0.01% vol.
HC	0–9999% ppm vol.	1.0 ppm vol.
O2	0–22% vol.	0.01% vol.
NO	0–5000 ppm vol.	1.0 ppm vol.
Diesel Smoke meter		
Degree of opacity	0–100%	1%
Absorption coefficient	0-10 m^{-1}	0.01m^{-1}

Table 3
Fatty acids methyl ester (FAME) compositions of biodiesel fuels (%w/w).

Fatty acids		WCOB [30]	LFB [31]	CFB [31]	KB [29]
C12:0	Lauric acid	0	0	0	0.26
C14:0	Myristic	0	2.2	0.04	0.25
C16:0	Palmitic	10.89	21.1	21.6	10
C16:1	Palmitoleic acid	0	2.1	3.2	0.71
C18:0	stearic acid	7.89	11.16	6.3	4.5
C18:1	Oleic acid	53.56	38.7	30	40.21
C18:2	Linoleic acid	21.34	10.2	28.4	22.36
C18:3	Linolenic acid	2.09	0.6	2.4	3.76
C20:0	Arachidic acid	1.82	0	0	0.22
C20:1	Gadoleic acid	1.15	0	0	0.26
C22:0	Behenic acid	4.11	0	0	0.21
C22:1	Erucic acid	0	0	0	0.2
C20:4	Arachidonic acid	0	0	3.4	0
C22:5	Docosapentaenoic acid	0	0	0.3	0
C22:6	Docosahexaenoic acid	0	0	0.8	0
C24:0	Lignoceric acid	1.33	0	0	0

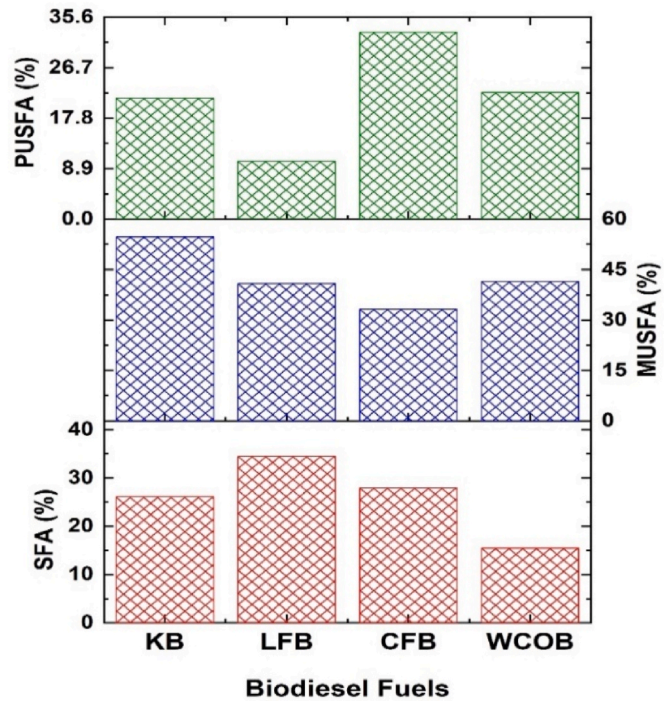

Fig. 3. Fatty acids compositions of various biodiesels.

$$\text{MUSFA } \% = \sum \textit{One double bons chain } (C=C) \textit{ in FAs} \quad (4)$$

$$\text{PUSFA } \% = \sum \textit{More than one double bons chain } (C=C) \textit{ in FAs} \quad (5)$$

3.2. Engine performance

The power produced by the fuel were analysed as engine output power in terms of engine performance. In this section, effect of engine coolant temperature on brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC) were discussed at different engine loads.

3.2.1. Brake thermal efficiency

The heat equivalent of brake power to the heat equivalent of the fuel consumed is described as brake thermal efficiency (BTE) or fuel conversion efficiency. It is observed that BTE for biodiesel fuel increased with increases in the coolant temperature from 65 to 85 °*C* at both the torques (23.5 Nm & 18.5 Nm); and they were relatively higher than diesel fuel (Fig. 4). It is due to increased in-cylinder temperatures and fuel bound oxygen present in biodiesels. Higher in-cylinder temperature improved the fuel atomisation, vaporisation and fuel/air mixing rate, which results better combustion efficiency [6]. It was observed that LFB shows higher BTE at higher coolant temperatures at both torques. They were about 4% and 5% higher than diesel fuel at full load (23.5 Nm) and part load (18.5 Nm). Higher BTE for LFB is due to higher SFA%,which led to increased carbon/oxygen (C/O) ratio [19] and decreased viscosity (Table 4). Lower viscosity and higher oxygen % along with higher coolant temperatures improved fuel/air mixing rate and combustion performance of LFB [10].

3.2.2. Brake specific fuel consumption

The brake specific fuel consumption (BSFC) is a measurement of how efficiently an engine uses the fuel. Not much variation was observed in BSFC with increases in the engine coolant temperature from 65 to 85 °*C* at both loads. For a single fuel, BSFC was reduced at full load (23.5 Nm), because at full load, fuel/air ratio was reduced due to higher amount of fuel is required to maintain the engine torque [6]. BSFC for all the tested biodiesel fuels were found to be higher than the diesel fuel due to lower CV and higher viscosity values as compared to diesel (Table 4). At full load (23.5Nm), the BSFC for LFB was observed to be decreased by 0.81% and 1.3% at 85 °C, and 0.88% and 0.8% at 65 °C, as compared to WCOB and KB respectively (Fig. 5). Lower BSFC of LFB than other biodiesel fuel is mainly due to differences in the fuel properties, such as lower viscosity, and higher SFA%. Higher SFA% increases the oxygen % and hence improves fuel efficiency. Sharma et al., [19] investigated the effect of different biomix fuels on SFA% and fuel properties. They reported that increases in the SFA level of the biodiesel fuel increases the oxygen % due to shorter C-C chain and fewer C=C double bond % [19].

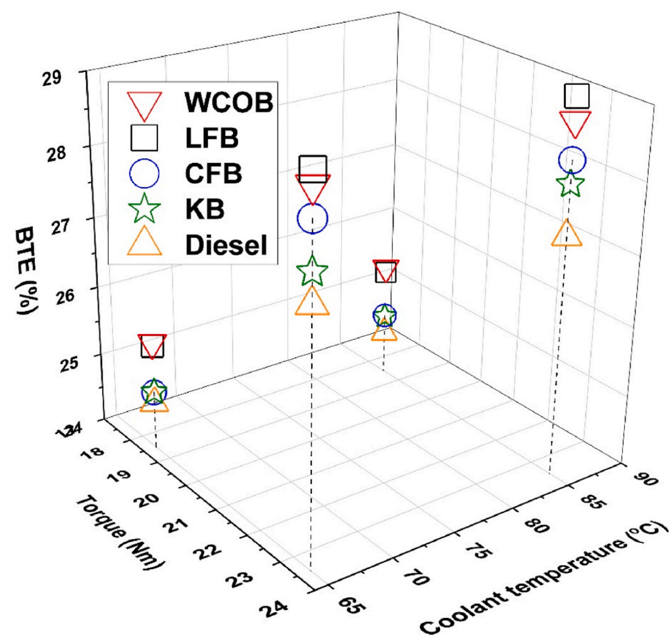

Fig. 4. Brake thermal efficiency vs. torque and temperature.

Table 4
Biodiesel fuel properties.

Properties	WCOB	LFB	CFB	KB	Diesel	EN 14214	ASTM D6751-08
Viscosity at 40 °*C* (cSt)	4.16	3.45	4.2	4.52	2.65	3.5–5	1.9–6
Density at kg/m^3	882	887	874	883	833	860–900	820–860
HHV (MJ/kg)	38.821	39.621	40.42	40.87	44.32	–	–
Flash Point (°*C*)	165	135	125	165	64	120 mini	93 mini
Cetane number (CN)	56[a]	59[b]	57[c]	55[a]	56[d]	51mini	47 mini
AV (mgKOH/g)	0.4	0.23	0.26	0.55	0.02	0.5 max	1.5 max

*HHV- higher heating value, AV-acid value.
[a] :reference [29].
[b] :reference [31].
[c] :reference [32].
[d] :reference [19].

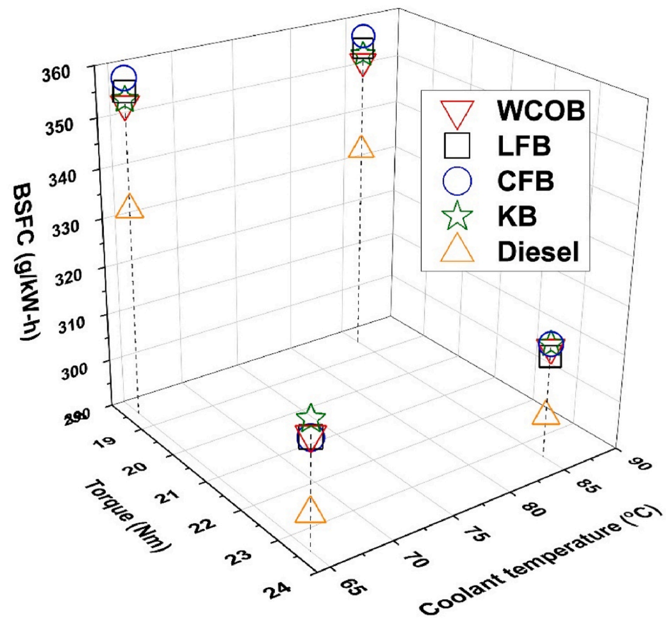

Fig. 5. Brake specific Fuel consumption (BSFC) vs. torque and temperature.

3.2.3. Exhaust gas temperature

Exhaust gas temperature (EGT) is critical for heating applications, after treatment and NOx emission control. As the temperature of the cooling water was raised, EGT rose for all engine loads (Fig. 6). At both engine coolant temperature and load, EGT for biodiesel fuel was found to be lower than diesel fuel.

3.3. Emission characteristics

Emissions produced by the combustion of any modified alternative fuels are vital and ideally should be lower than diesel fuel emissions. In this section NO, CO, CO_2, HC and smoke formation from the four different biodiesels at different coolant temperature was discussed.

3.3.1. Carbon monoxide

Carbon monoxide (CO) is produced as a by-product of the carbon dioxide production process. Lack of oxygen or excessively low temperatures can prevent CO from being oxidised into CO_2. As demonstrated in Fig. 7, these two factors contribute to a decrease in CO emissions as the coolant temperature rises. It was observed that CO emissions were increased by lowering the coolant temperature from 85 to 65 °*C*. The WCOB and CFB shows 11% increment, LFB and KB shows 14% and 10% increment. Whereas fossil diesel shows 50% increment in CO emissions while decreasing the temperature from 85 to 65 °*C*. It is due to fall in in-cylinder temperature which slowdown the CO_2 formation rate. At full load (23.5Nm), CO emission for LFB was observed to be 25% and 22% lower than WCOB at coolant temperature of 85 °*C* and 65 °*C* respectively. Whereas CO for LFB was 86% and 85% lower than KB at 85 °*C* and 65 °*C*. Moreover, CFB shows comparable results at both coolant temperatures when compared to WCOB, but it was found 81% lower than KB at both the coolant temperatures. At part load, LFB shows 40% and 78% lower CO at 85 °C and 33% and 80% at 65 °C, as compared to WCOB and KB. Whereas CFB shows 64% and 70% lower CO emission than KB at 85 °*C* and 65 °*C* but equivalent to WCOB at both the coolant temperatures. The CO for WCOB and KB was found to be higher than LFB and CFB due to higher number of double bonds (higher USFA). Higher USFA content increases the boiling point of non-edible based biodiesel fuels and reduces the oxidation rate of CO to CO_2 [30].

3.3.2. Carbon dioxide

Fig. 8 shows carbon dioxide (CO_2) fluctuation when different cooling temperatures are used. Complete combustion resulted from the increased cooling temperature produces additional heat within the engine cylinder. Due to the increased heat release values of diesel fuel, CO_2 levels rise as engine loads and speeds rises. It was found that CO_2 emission for the tested fuels were increased by about 0.5–1.7% at both the torques (23.5 Nm & 18.5Nm) and coolant temperatures (85 °*C* and 65 °*C*). At full load (23.5 Nm), CO_2 for LFB and CFB were found 0.1% and 2% higher than WCOB, and 5% and 3% lower than KB at coolant temperature of 85 °*C*. Whereas, at coolant temperature 65 °*C*, CO_2 for LFB and CFB were found to be 0.3% and 2.2% higher than WCOB and 4% and 2% lower than KB. While reducing the engine torque to part load (18.5Nm), CO_2 formation for LFB and CFB were observed to be 0.2% and 2% higher than WCOB, and 6% and 4.3% lower than KB at coolant temperature of 85 °*C*. At coolant temperature 65 °*C*, CO_2 emission for

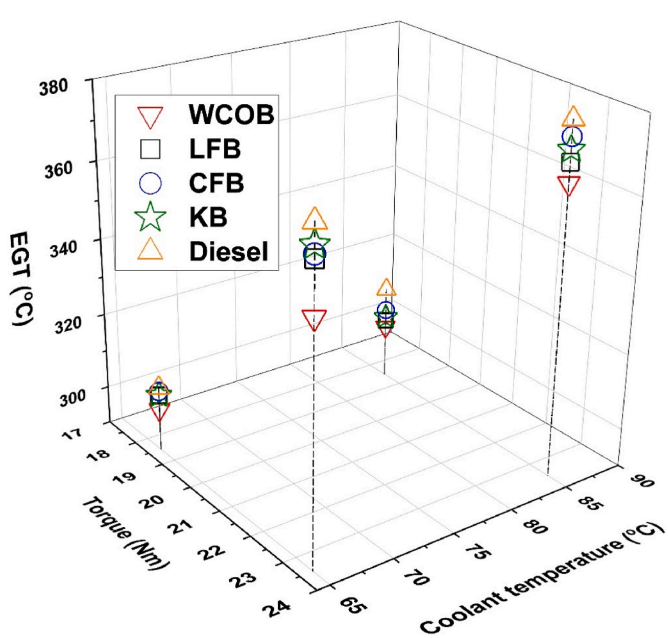

Fig. 6. Exhaust gas temperature (EGT) vs. torque and temperature.

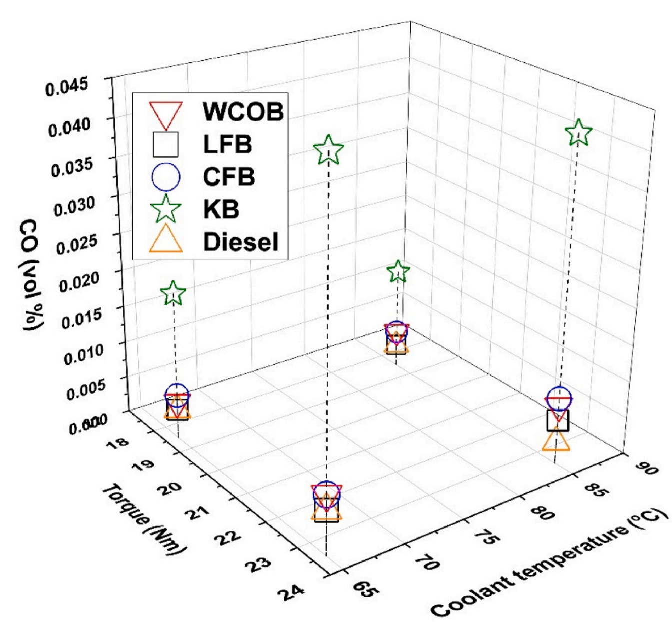

Fig. 7. Carbon monoxide (CO) vs. torque and temperature.

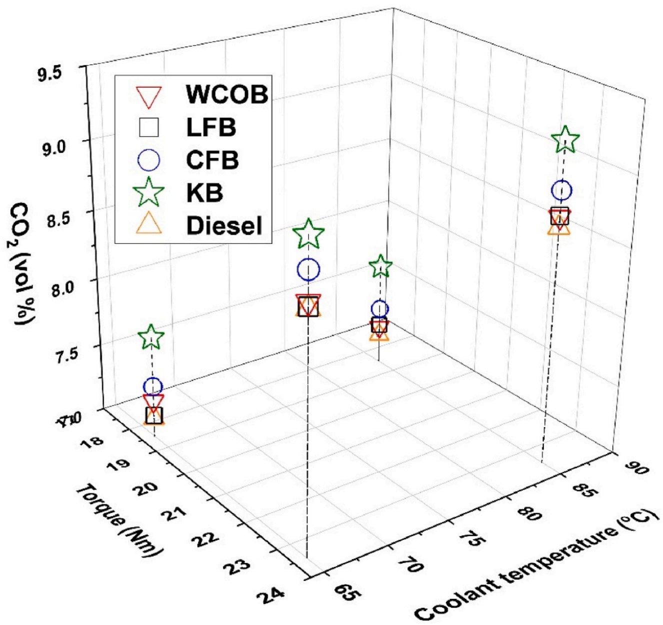

Fig. 8. Carbon dioxide (CO_2) vs. torque and temperature.

LFB and CFB were observed to be 1.5% higher than WCOB; and 7% and 4% lower as compared to KB at part load (18.5 Nm) respectively. It was noticed that LFB and CFB shows lower CO_2 emissions as compared to WCOB & KB due to higher saturated fatty acid (SFA %). Higher SFA content reduced the boiling point of biodiesel fuel and accelerated the CO_2 formation rate [30].

3.3.3. Oxides of nitrogen

Nitric oxide (NO) formed when the temperature in the combustion chamber becomes too high. At high temperatures, nitrogen and oxygen react to form nitrogen oxides in a fuel/air combination with a high fuel/air ratio due to the zeldovich mechanism, which refers to thermal NO formation [23]. The temperature in the cylinder, the ignition time, and the oxygen concentration all has a role in the creation of NO emission [33]. As illustrated in Fig. 9, the experimental findings revealed a rise in NO with increasing coolant temperature 65-85 °*C*, and at both torques (23.5 Nm & 18.5 Nm). The formation of NO emissions for all biodiesel samples were increased by 1–2.4% and reduced by 3.5% for fossil diesel while the coolant temperature was increased from 65 to 85 °*C* at full load (23.5Nm) condition. The reason for reducing the NO formation for fossil diesel is due to lack of oxygen % at higher load and shorter combustion duration [33]. The NO levels rise when the engine coolant temperature rises, owing to an increase in the charge temperature, which raises the burnt gas temperature, resulting in a rise in thermal NO emissions. At full load (23.5 Nm), it was found that NO emissions for LFB and CFB were observed to be lower by 22% and 19% as compared to WCOB, and by 24% and 20% than KB at coolant temperature of 85 °*C*. Whereas at coolant temperature 65 °*C*, it was further reduced by about 22% and 21% than WCOB, and 23% and 22% as compared to KB respectively. At part load (18.5 Nm) condition, NO formation for LFB and CFB were observed to be lower by 19% and 20% than WCOB and KB at coolant temperature 85 °*C*. The NO formation for LFB and CFB were also found lower by 21% and 20% than WCOB and 23% and 22% than KB at coolant temperature 65 °*C* respectively. It was noticed that 1–5% increment in NO formation were observed for all tested fuels while changing the coolant temperature from 65 to 85 °*C* at low load (18.5 Nm). LFB & CFB fuel consists of higher saturated fatty acids (SFA%) as compared to WCOB and KB. Hence it clearly observed that fuel rich with SFA% produced lower NO gas emissions [30].

3.3.4. Hydrocarbon emission

The emission of hydrocarbons (HC) is mostly caused by partially burned and unburned hydrocarbons that are unable to mix with oxygen gas [34]. As a result, the combustion process becomes incomplete. Fig. 10 shows the effect of coolant temperatures on HC emissions at different loads [14]. It was observed that HC emission increased with increases in the coolant temperatures. The CFB showed 50% reduction in HC when the coolant temperature was increased to 85 °*C*. KB gave higher HC emission as compared to all biodiesel and fossil diesel (Fig. 10). At part load (18.5 Nm) condition, HC were found to be decreased while the coolant temperature was increased (65-85 °*C*) for biodiesel fuels and it was found to be lower than fossil diesel due to higher availability of oxygen [35].

3.3.5. Smoke emission

Smoke emission is a visible indicator of the incomplete combustion due to the presence of rich fuel-air mixture [35]. Smoke emissions for all biodiesel fuels were found to be lower than fossil diesel fuel due to better combustion because of higher oxygen % in biodiesel fuel [30]. It was observed that the smoke level decreases with increase in the engine coolant temperature (65-85 °*C*) at both the torques (23.5 Nm & 18.5

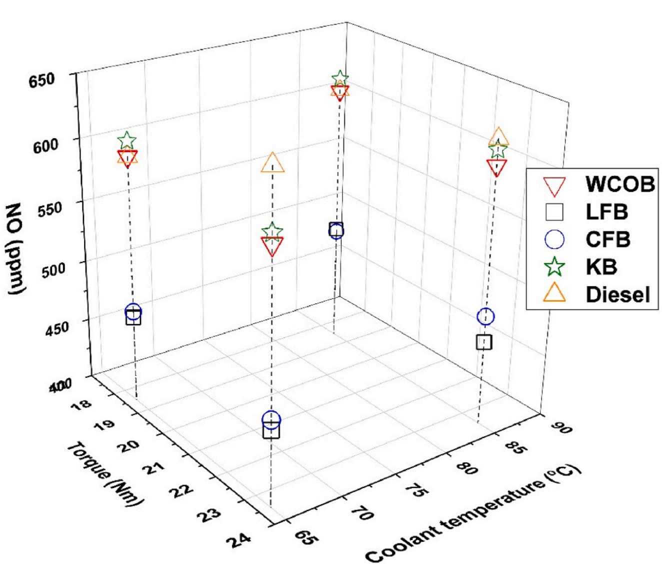

Fig. 9. Oxides of nitrogen (NO) vs. torque and temperature.

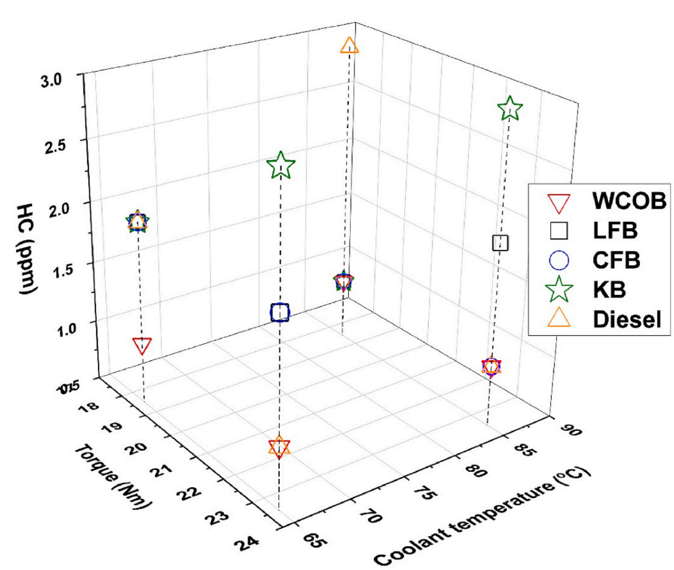

Fig. 10. Hydrocarbon (HC) vs. torque and temperature.

Nm) (Fig. 11). About 6–15% reduction at full load (23.5 Nm) and 11–50% reduction in smoke at part load (18.5 Nm) was observed. It was noticed that both the animal fat (LFB & CFB) showed lowest smoke emission as compared to WCOB and KB (Fig. 10) due to higher SFA% (Fig. 3), cetane number (CN) and lower viscosity (Table 4). Lower viscosity and higher CN improve the combustion efficiency which resulted lower smoke emissions [29].

4. Conclusions

Engine out emissions are strongly influenced by engine operating parameters and fuel properties. Limited studies on the effect of engine coolant temperature on biodiesels combustion and emissions area available in literature. Whereas studies on detailed analysis of FAME%, and effects the SFA and USFA level on engine performance and emissions at different engine coolant temperatures and loads is missing. To fulfil this knowledge gap, two-cylinder diesel engine was operated at full load (23.5 Nm) and part load (18.5 Nm) conditions by changing the coolant temperature 65 $^{\circ}C$ and 85 $^{\circ}C$. Four different biodiesels were used in the study. The main findings of the study are drawn as follows:

1) Biodiesels fuel was prepared from the waste feedstocks such as waste cooking oil, animal fat (lamb and chicken) and non-edible oil (Karanja). Their physical properties were characterised, and fatty acids compositions were analysed
2) Lamb Fat and chicken fat shows higher SFA% whereas Karanja and chicken fat shows higher unsaturation levels. Chicken fat was found in optimum level of fatty acids.
3) BTE for biodiesel fuel increased with increase in coolant temperature due to higher oxygen % whereas not much variation was observed in BSFC with increases the coolant temperatures from 65 to 85 °C at both the loads.
4) CO and CO_2 emissions for tested fuels were increased with the increases in the engine coolant temperature (65 °C and 85 °C) and load (18.5 Nm and 23.5 Nm). At full load, LFB and CFB shows lower CO emission than WCOB and KB by about 25% and 86%. Whereas CO_2 emissions were found to be 0.1–2% and 3–5% lower than WCOB and KB due to higher SFA % and lower viscosity of LFB and CFB.
5) The NO emissions for all the tested biodiesel samples were increased by about 1–2.4% but it was reduced for diesel fuel by 3.5% while the coolant temperature was increased from 65 to 85 °C at full load (23.5 Nm). At full load and at 85 °C, LFB shows 22% and 25% lower NO than WCOB and KB fuels. This can be correlated with the exhaust gas temperature. EGT was found higher for all the tested biodiesel fuel due to better combustion because of higher oxygen content. KB shows the lower EGT as compared to other higher SFA fuel.
6) HC and smoke emission increased with increases in the coolant temperatures. At full load, LFB shows higher HC emissions as compared to other biodiesels due to longer carbon chain. Animal fat biodiesels shows lower smoke emission by about 6–15% at full load (23.5 Nm) and 11–50% at part load (18.5 Nm) condition when compared to WCOB and KB fuels (Fig. 10) due higher SFA%, cetane number (CN) and lower viscosity. Lower viscosity and higher CN improve the combustion efficiency which resulted lower smoke emissions.

Overall, it can be concluded that coolant temperature does have significant influence on engine performance parameters, and exhaust emission, which also depends on the type of fuels and their physical and chemical properties. Higher SFA% fuel shows overall better performance. Recommendation for optimising the fuel additive and high SFA biodiesel emulsion and nanoparticle addition on engine cooling effect would be the future scope of the study.

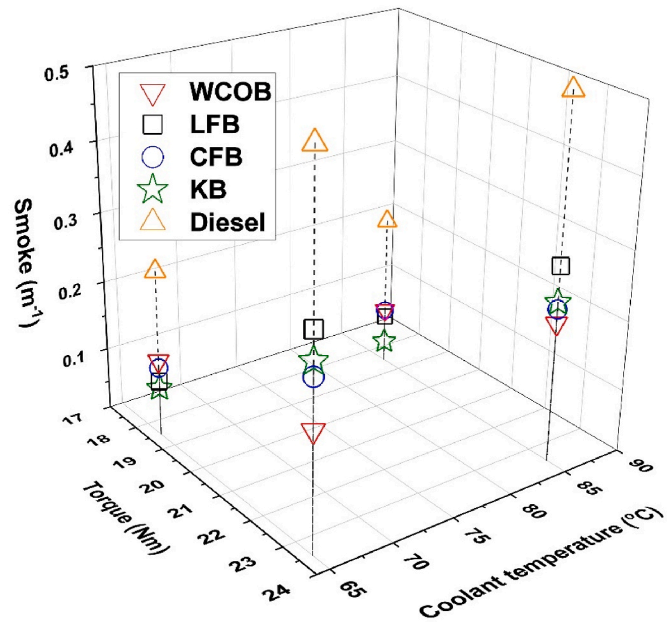

Fig. 11. Smoke emissions vs. torque and temperature.

CRediT authorship contribution statement

Abul K. Hossain: Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition, Visualization, Data curation. **Vikas Sharma:** Conceptualization, Methodology, Investigation, Formal analysis, Resources, Data curation, Writing – original draft, Visualization. **Gulzar Ahmad:** Conceptualization, Resources, Investigation, Formal analysis, Writing – original draft, Analysis, Writing - Draft, Visualization. **Tabbi Awotwe:** Conceptualization, Methodology, Investigation, Supervision, Writing – original draft, Writing - Draft.

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.

Data availability

Data will be made available on request.

Acknowledgement

This study is the extended version of the work, presented at 5th SEE SDEWES hybrid conference held on 22–26 May 2022 in Vlorë, Albania. We acknowledge the funding provided by the UKIERI project (Grant Number: DST-UKIERI 18-19-04).

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