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Assessment of diesel engine performance and emission using biodiesel obtained from eucalyptus leaves

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ABSTRACT

Hunger for energy consumption is booming due to industrialization and globalization causes the consumption of fossil fuel resources and searching for unconventional fuels. Among all other available unconventional fuels, biodiesel has achieved significant considerations globally. The present research is catering production of biodiesel from eucalyptus species as forest waste using fast pyrolysis. The derived biodiesel was tested for its various physical and chemical properties using standard test methods (IS 1448, ASTM D 4868). The major properties of the derived biodiesel are similar to the existing diesel fuel. The obtained biodiesel is having a cetane number of 54, the kinematic viscosity of 5.83 cSt, and a calorific value of 7,850 kcal/kg. The derived biodiesel was tested in a fixed compression ratio diesel engine. The variable parameters were blending ratio and engine load. The engine gave the best performance at B100 with full load gave the highest 33.57% BTE, 0.31 kg/KWhr of lowest SFC, and minimum ignition delay. Its emission characteristics also follow current exhaust gas emission norms as per BS6 in India. NO_x emission was a minimum of 235 ppm at B100, hydrocarbon emission was a minimum of 0.038 g/KWhr at full load with B100 and the least CO emission of 2.85 g/KWhr was observed at full load with pure biodiesel (B100). Thus, obtained biodiesel can be used as a fuel in the CI engine as an alternative source of energy.

Keywords: energy, fossil fuel, biodiesel, cetane number, pyrolysis, emission norms

INTRODUCTION

The increase in demand for energy consumption due to consistent reduction in fossil fuel resources is the driving force in producing and utilizing unconventional fuels. Among all other available unconventional fuels, biodiesel has achieved significant consideration globally (Jani, 2019; Patel et al., 2020). Being a renewable resource, biodiesel has various benefits, such as the potential for waste sources recycling, and the ability of emission reduction as compared to conventional diesel (Patel et al., 2009a; Simsek, 2020). Various types of feedstock producing biodiesel, which are the most utilized resources on a large industrial scale are known to have higher quality edible oils (Kumar & Sharma, 2015; Patel et al., 2009b). This is important for supply chain security and its fewer constituents in free fatty acid (FFA). The ability of the current methods maintained at a particular level in the feedstock supply chain is the topic of hot discussion because it harms the hygiene of the food in the forthcoming years. Researchers have studied and reported various alternative feedstock to test the viability in the literature. The investigation was related to non-edible oil-bearing plants, such as Curcas, Jatropha, Soapnut, and Castor beans (Atmanli et al., 2015; Algayyim & Wandel, 2020; Ma et al., 2015), as well as non-edible waste fat from animal carcasses (Balamurugan & Nalini, 2016; Mwangi et al., 2015). BS-6 emission norms are implemented in India since January 2022.

In terms of industrial scale, transesterification is known as the most popular method to convert raw material in terms of oil or fat into biodiesel. In the current scenario, the majority of the commercially produced biodiesel uses alkali-catalyzed transesterification due to its fast reaction rate and requirement for low temperature and pressure (Shrivastava et al., 2019). Whenever FFA is found higher in feedstock, a process known as esterification is applied to transform the excessive fatty acid into methyl ester, which is one of the reasons for an increase in the overall processing cost. The above method is crucial but essential because without following it, it may tend to form a large amount of long-chain FAME, which results in poor low-temperature properties of the biodiesel produced, and reduced biodiesel yield as well (Wu et al., 2015).

Recent advancement in growing the transesterification method has been reported by researchers (Shuai et al., 2017) by which we can range from the use of non-catalytic microwave, supercritical alcohol, and ultrasound-assisted

Table 1. Physical properties eucalyptus biodiesel and its specific requirements

No	Chemical parameter	Specified requirement	Eucalyptus biodiesel	Diesel as a CF	Test method
1	Flash point (°C)	Min. 120	60	68-70	IS 1448 (PART-21):1992
2	Density at 15 °C (kg/m^3)	860-900	790	820-860	IS 1448 (PART-16):1990
3	Kinematic viscosity at 40 °C (cSt)	2.5-6.0	5.83	2.5.-6	IS 1448 (PART-25):1976
4	Cetane number	Min. 51	54	Min.46	IS 1448 (PART-9)

Note. CF: Conventional fuel

transesterification to plasma reactor technology. Though, the issues related to energy consumption, scale-up, and equipment cost are still under investigation.

In contrast, the pyrolysis method applied to animal fat and oil was reported (Kavitha & Murugavelh, 2019; Krishnamurthy et al., 2020; Patel et al., 2020) in which the thermal decomposition is applied to the objects at a very high temperature restricting the presence of oxygen for the production of biodiesel suits to diesel engines. Verified professional tools and techniques for the production of bio-oil from waste materials and biomass materials using the pyrolysis process have been in practice for a long time. These tools and techniques may work as a substitute for transesterification because it has flexibility in feedstock and compliance with the prevailing structure (Mathew & Anand, 2021). The potential driving force behind the growth of current research is the pyrolysis of biomass and other solid waste (Balat et al., 2009; Patel et al., 2019; Rajak & Verma, 2018). Researchers reported good properties found in the production of bio-oil using pyrolysis as compared to the transesterification approach (Arunkumar et al., 2019; Nanthagopal et al., 2018; Sani et al., 2018). Further, the constituents of the biofuel produced may be adjusted by varying the processing parameters in such a way that it permits a process to modify the products for specific uses (Ashraful et al., 2014).

The influence of biodiesel mixtures on the performance and emission of diesel engines is a matter of further investigation work for many years, as discussed in (Bragadeshwaran et al., 2018; Karthickeyan, 2018). The majority of all the research work involved in biodiesel production from the transesterification process is due to its popularity as discussed above. Limited data is available related to engine tests using a high amount of mixture ratio of nearly 100% biodiesel. It is concluded from the study that the produced biodiesel using varieties of feedstock may be useful to run traditional diesel engines using a blend ratio of nearly 20% with or without slight changes. A large variation was evident in processing parameters, feedstock, and the type of engine and improver materials used; therefore, the authors reported a general view on engine performance and emission. It is observed from the literature review that limited work is done to test engines using biodiesel under the pyrolysis process.

In this study, biodiesel was obtained from the eucalyptus leaves as forest waste in India through a fast pyrolysis process (Patel et al., 2021). The properties of eucalyptus biodiesel and its specific requirements are shown in **Table 1**. The similarity is found in density, heating value, and corrosiveness between biodiesel and conventional diesel. Due to having a negligible difference in density, it is possible to mix both the conventional diesel and biodiesel without separating them. It is also evident that fuel can be atomized effectively if the biodiesel has low density and viscosity. Further, starting the engine in cold weather is found easy as the pour point of the biodiesel is low. Further, biodiesel possesses the least amount of sulfur, which results in low emissions of hydrocarbons (HCs). On the other side, a high percentage of carbon is found in the biodiesel due to the pyrolysis process. Also, the calorific value (CV) of the biodiesel increases with an increase of HCs.

Biodiesel is developing as one of the most favorable alternative fuels that can replace the conventional diesel for use in compression ignition (CI) engine as renewable fuel with comparatively lower exhaust gas emissions, degrade easily biologically, and has organic carbon as a result of the photosynthetic process.

Moreover, conventional engines are found compatible with biodiesel without any major changes in it. Biodiesel is made from animal fat, vegetable oil, etc. falls under the standard ASTM D6751 and they are derived from the chemical reaction, the standard of European countries (EN) 14214 and Indian standards (IS) 15607:2005 for use in CI engine (Saravanan et al., 2018; Shuai et al., 2017). The Indian government initiated research on the first-generation edible oil resource for engine fuel applications by launching a national biodiesel policy in 2005 (Bragadeshwaran et al., 2018). Presently, the investigation of the third group of biodiesel resources is at the beginning. Therefore, one possible choice for biodiesel production is to use non-edible oil harvests. The eucalyptus tree is a source of non-edible oil and capable to grow in all climatic conditions and in all regions in India. Eucalyptus oil is available throughout the year, and it was derived from the leaves and barks of the tree. Biodiesel is safer to transport or handle than petroleum diesel as it has a relatively high flash point, and it is less volatile. Due to its lubricating properties, engine wear and long engine life are advantages of bio diesel. In the present work, eucalyptus leaves were selected as feed stock materials for the production of bio diesel. Still, it is a challenge to fulfil the requirement of energy for transportation by using only non-edible oils and for compensation against food crises.

Many experiments have been accomplished to check the compatibility of biodiesel and its mixture for CI engine applications (Abed et al., 2018; Sridhar et al., 2020). Biodiesel reduces pollution and greenhouse gas emissions (GHG) (Ashraful et al., 2014). A high amount of the brake specific fuel consumption (BSFC) and NO_x emissions were observed during trials (Algayyim & Wandel, 2022; Manigandan et al., 2019; Nik-Azar et al., 1997); still, substantial reduction of carbon monoxide (CO), unburned HC, and smoke emissions was found using biodiesel and their mixtures as compared to diesel (Leite et al., 2019; Mahalingam & Ganesan, 2020). The combustion characteristics in terms of ignition delay, peak pressure, heat release rate, etc. were separated using biodiesel as compared

Figure 1. Experimental engine setup (Photograph, I.C. Engine Laboratory, G.E.C. Godhra)

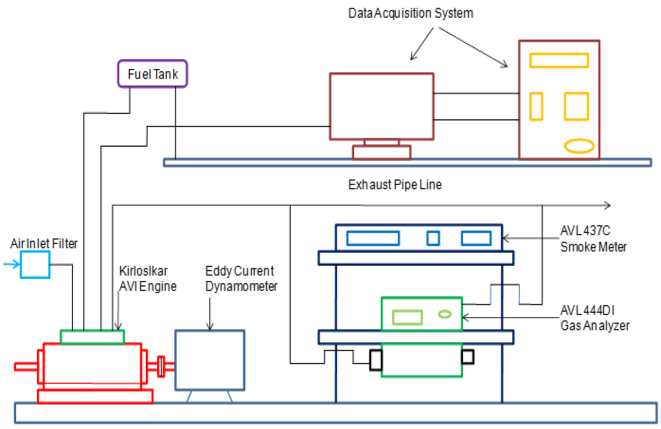

Figure 2. Line diagram of the experimental setup (Source: Authors' own elaboration)

to conventional diesel (Rajak et al., 2018). The application of biodiesel derived from waste cotton oil in CI engines reported an increase in fuel consumption and NO_x emission, whereas HC emission and smoke opacity were reduced significantly (Kana & Shaija, 2020). A wide range of experiments were conducted to check the feasibility of the production and applications of various biodiesels. The results of the current study will be comprised of getting attention to biodiesel and targeting the disposal issues.

The objective of this research work is to study the effect of biodiesel achieved using pyrolysis of eucalyptus leaves. A CI engine was selected to check its performance. In this work, eucalyptus leaves as wastage were collected from the forest. First, they were mixed and cleaned properly. The biodiesel was produced using equipment called a pyrolysis rig. The effect of the compound and its intensity on the pyrolysis temperature along with biodiesel yield were examined. Testing of biodiesel was conducted on a diesel engine, using blend ratios from 0% (B0) to 100% (B100). A graphical comparison is made between the performance of engine emissions and combustion characteristics for biodiesel mixture and crude diesel keeping the aim to have an optimum combination.

Table 2. Technical specifications of the engine

Parameters	Value
Type of engine	4-stroke
Number of cylinder	1
Cylinder diameter (D)	0.0875 meters
Cylinder stoke (L)	0.0800 meters

EXPERIMENTAL SET UP FOR ENGINE TEST

The testing of the biodiesel and its mixtures were done in a single cylinder, four stroke, air-cooled, direct injection diesel engine. A device named a tachometer was used for the measurement of engine speed. The experimental engine setup is shown in **Figure 1**; a schematic of the engine test is presented in **Figure 2**, whereas the technical terms of the engine are presented in **Table 2**. For the measurement of brake power, a DC generator was used with a load controller having a maximum electrical power output of 10.5 KW coupled with an engine. The pressure drop was measured using a differential manometer and thus the intake airflow rate was calculated before flowing into the engine. To measure temperature at various locations in the engine, calibrated K-type thermocouples were used. At the beginning of every trial, the engine was allowed to run for around 20 min. so that the steady-state condition can be attained before the actual experiment starts. Afterward, fuel having a volume of 30 cm^3 was used for each trail, which is used to calculate the average fuel flow rate. The injection pressure of the fuel was set by adjusting the spring tension of the fuel injector.

A pressure transducer working on piezoelectric principle (model 601A) made of Kistler coupled with a Nexus charge amplifier (2692-A-0S4) was used for the measurement of in-cylinder pressure. This is for achieving minimum lag in the pressure signal and to avoid resonance caused by the connecting pipe. A proximity switch was used to fix the position of the top dead center of the piston, and it is fitted on the output engine shaft. The combustion pressure data were averaged over 120 successive engine cycles. LABVIEW software and a data acquisition card (NI-USB-6210) were used for data acquisition. An AVL 437C smoke meter and AVL 444DI gas analyzer were used for smoke opacity and exhaust gas emissions concentration measurements, respectively. The experiments were performed at 25%, 50%, 75%, and 100% load with engine speed at 1,500 rpm.

EXPERIMENTAL TEST PROCEDURE

Experiments were performed using conventional diesel and biodiesel blends produced from waste eucalyptus leaves at a constant speed, varying load conditions from idle to full load. The rated speed of the engine was maintained at 1,500 rpm. After getting the fluctuations in the range of ±2.5% of the rated speed, the test data were recorded. To avoid the possibility of mixing fuels during the test, the fuel line was drained

Table 3. Experimental parameters and values

No	Parameters	Value
1	Dynamometer arm length (L)	0.1850 m
2	Cylinder bore (D)	0.0875 m
2	Number of cylinder (C)	01
3	Orifice diameter (d)	20 mm
4	Orifice coefficient of discharge (Cd)	0.605
5	Ambient temperature	250 °C
6	Flow rate of water in engine	250 lit/hr=0.0694 kg/sec
7	Flow rate of water in calorimeter	100 lit/hr
8	CV_{BO}	42,850 kJ/kg
9	CV_{B20}	30,491 kJ/kg
10	CV_{B40}	31,140 kJ/kg
11	CV_{B60}	31,966 kJ/kg
12	CV_{B80}	324,170.20 kJ/kg
13	CV_{B100}	32,868.60 kJ/kg
14	ρ_{BO}	833 kg/m³
15	ρ_{B20}	742 kg/m³
16	ρ_{B40}	751 kg/m³
17	ρ_{B60}	756 kg/m³
18	ρ_{B80}	773 kg/m³
19	ρ_{B100}	790 kg/m³

completely before the starting of each trial. Similar operating conditions were kept for all the trials to obtain consistency in results.

Observations and Computations

Table 3 represents the data available for the test setup engine.

Sample calculation for run (% blending=40, load=11 kg.f (100% load, full load), injection pressure=240 bar, compression ratio [CR]=17.5) is shown for the constant speed engine.

Uncertainty Analysis

Uncertainty or error analysis is required to make the standard calculation by the test method accurate. Perform this analysis five times and take the average to calculate the test result. Some of the errors discussed in this study are environmental condition, observer error, accuracy of equipment, calibration, and conducting experimenting using instrument. The uncertainty analysis for different measuring quantities was estimated based on the error that is listed in Table 4 using the following error relation. The overall uncertainty of the experiment was obtained, as given in the following equation, percent of uncertainty (POU):

$$POU=\sqrt{\begin{matrix}TIS^2+SS^2+LCS^2+PTS^2+CAE^2+LFR^2+\\HVM^2+(SM)^2+(CO_2)^2+(NO_x)^2+CO^2+HC^2\end{matrix}}=$$

$$\sqrt{\begin{matrix}0.15^2+1^2+0.2^2+0.5^2+0.2^2+0.5^2+1^2+\\1^2+1^2+0.5^2+0.3^2+0.1^2\end{matrix}}=2.23\%,$$

where TIS is temperature indicator sensor, SS is speed sensor, LCS is load cell sensor, PTS is pressure transducer sensor, CAE is crank angle encoder, LFR is liquid flow rate, HVM is heat value measured, and SM is smoke meter.

Table 4. Instrument & uncertainties of experimental test engine

No	Instruments	Uncertainty in %
1	Temperature sensor	Temperature sensor ±0.15%
2	Speed sensor	±1.0%
3	Load indicator	±0.2%
4	Pressure sensor	±0.5%
5	Crank angle encoder	±0.2%
6	Fuel measuring	±0.5%
7	Heat value measured	±1.0%
8	Smoke meter (AVL 437C)	±1.0%
9	AVL 444DI gas analyser	
	CO_2	±1.0%
	NO_X	±0.5%
	CO	±0.3%
	HC	±0.1%

The calculation is based on value for overall uncertainty and is found to be ±2.23%, which is in the range of acceptance for the experimental work.

Sample calculation for heat balance sheet (SET-1) is, as follows:

Total heat supplied=mf×CV=0.92×42,140=38,750.4 kJ/hr.

Heat utilized to produce brake power=BP×3,600=3×3,600= 10,800 kJ/hr.

Heat carried by cooling water=flow rate of cooling water (lit/hr) × C_p × (t_2-t_1)=250×10-3 (m³/hr) × 1,000 (kg/m³) × 4.187 (kJ/kgK) × (46.5-30.19) (K) = 17,072.49 kJ/hr.

Heat carried by exhaust gas=mw×Cpw×(Two-Twi) + m_g × C_{pg} × (t_5-t_{amb}),

where Two is outlet temperature of water circulated through exhaust gas calorimeter=t_4, K, Twi is intlet temperature of water circulated through exhaust gas calorimeter=t_3; K, A is F ratio=24.22:1.

Heat carried by exhaust gases=25×4.187×(66.20-30.20) + (0.92+25.22)×1.005×(234-25)=7,846.97 kJ/hr.

Unaccounted heat losses = (heat supplied)-(1+2+3)= 38,750.4-(10,800+17,072.49+7,846.97)=38,750.4-35,719.46= 3,030.94 kJ/hr.

Table 5 represents the heat balance sheet for sample calculation.

RESULTS AND DISCUSSION

Engine Performance

Discussion of engine performance measurements such as exhaust gas temperature (EGT), brake thermal efficiency (BTE), specific fuel consumption (SFC), etc. describes CI engines loading at 25%, 50%, 75%, and 100% of the engine by eucalyptus biodiesel and its combinations with pure diesel.

Table 5. Heat balance sheet for sample calculation

Heat supplied	kJ/hr	%	Heat distributed	kJ/hr	%
Heat supplied by fuel	38750.4	100	(1) Heat Utilized to produce BP	10,800.00	27.88
			(2) Heat lost in cooling water	17,072.49	44.05
			(3) Heat in the exhaust gas	7,846.97	20.25
			(4) Unaccounted heat losses	3,030.94	7.82

Table 6. Performance parameters at full load for B0 and B20 blend ratio

Load (%)	Performance parameters					
	BTE (%)		SFC (g/KWh)		EGT (K)	
	B0	B20	B0	B20	B0	B20
25	16.66	13.57	523.52	600.00	437.23	434.04
50	28.09	27.38	300.00	323.52	496.80	486.17
75	31.90	31.42	270.58	282.35	560.63	554.25
100	34.76	34.28	252.94	264.7	632.85	620.00

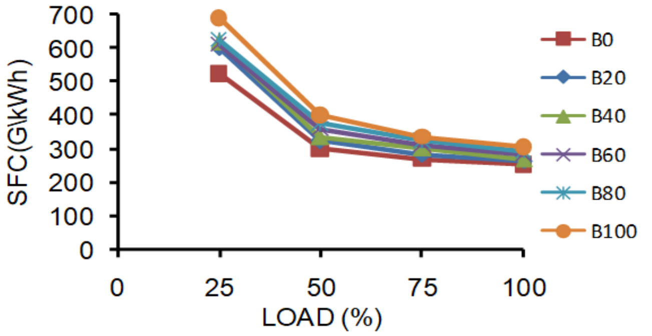

Figure 3. Specific fuel consumption vs. load at a constant 1,500 rpm (Source: Authors' own elaboration)

Performance metrics are summarized in **Table 6** for B0 and B20 mix ratio, 23.5 s injection timing, 1,500 rpm, and maximum load CR 17.5.

SFC directly depends on the characteristics of the fuel, such as CV, viscosity, and fuel density. They play an important role in fuel consumption and insufficient cleaning. A blind test was carried out using a variety of fuels, and the results showed that B20 has high performance and various biodiesel has high fuel consumption. Due to the high density of biodiesel, it has high viscosity, low heating value and biodiesel SFC is increased. **Figure 3** shows SFCs with different mixing ratios under different engine load conditions.

The result shows that the SFC of B0 is smaller than the SFC of B100. It is found that the SFC for B0, B20, B40, B60, B80, and B100 was 252.84 g/KWh, 264.5 g/KWh, 270.48 g/KWh, 282.25 g/KWh, and 294.151 g/KWh and 304.86 g/KWh, respectively. In eucalyptus biodiesel (B100), SFC is considered as the above comparison, and the positive performance value of B20 is 4.64% higher than that of diesel (B0).

Brake thermal efficiency

Figure 4 shows the change in BTE as a function of different engine load conditions for different fuel mixtures. Lower BTE efficiency can be associated with lower volatility, lower fuel CV, higher viscosity, higher fuel density, impairment of fuel formation during combustion, which leads to lower combustion. It has been shown that the BTE is lower compared to diesel fuel due to the decrease in the CV of the fuel with increased fuel consumption. Previous research found that an optimal B20 mix ratio would go a long way in a long-term study (Rajak et al., 2019).

The BTE of B0 (pure diesel) was relatively high compared to the B100. This is due to the less CV of eucalyptus biodiesel. For CR 17.5, there was a 0.63% reduction in motor BTE on B20 as compared to B0. The result showed that the BTEs for B0,

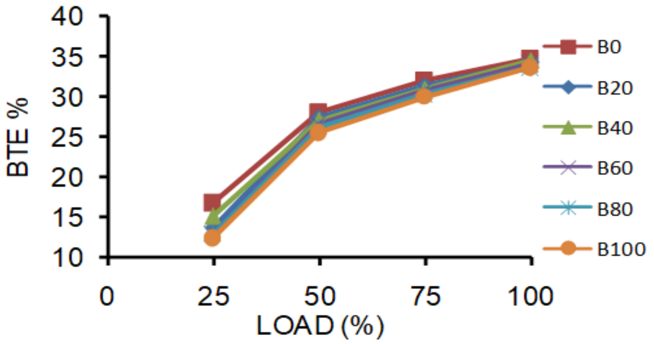

Figure 4. Brake thermal efficiency vs. load at 1,500 rpm (Source: Authors' own elaboration)

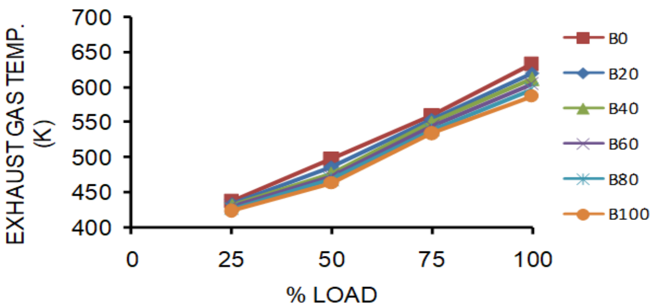

Figure 5. Exhaust gas temperature vs. load at 1,500 rpm (Source: Authors' own elaboration)

B20, B40, B60, B80, and B100 were 34.76%, 34.28%, 34.52%, 34.04%, 33.57% and 33.57%, respectively, at full engine load. Compared to B0 (pure diesel), the overall decrease in B100 efficiency was about 3.42%.

Exhaust gas temperature

Figure 5 shows the change in the average temperature of the exhaust gas depending on the various load conditions of the engine for mixing the air-fuel mixture. As the engine load increases, the average gas temperature rises. As the load on the engine increases, so does the amount of fuel that enters the engine cylinders, resulting in the engine producing more heat. When using biodiesel (B100), the average gas temperature is 7.20% lower than that of diesel (B0). The average EGT directly depends on the oxygen content of the fuel. Although the CV of biodiesel is much lower compared with diesel, the higher oxygen content in biodiesel leads to the first final combustion.

It is found that the average gas flow rate using B0 (pure diesel) is higher than that of B100. When using B0 at CR17.5, the gas temperature is 632.85 K, B20 is 620 K, B40 is 611.42 K, B60 is 604.28 K, B80 is 597.14 K, and B100 is 587.14 K. Reduce GHG is a good solution, B100 can reduce the production of NO_X in the engine. It is observed that the BTHE increases with an increase in engine load for all the blend ratios. A maximum of 62% of increment is evident in BTHE at full load as compared to minimum load value; see **Figure 4**. The optimum value of an engine load is attained at approximately 75% of full load capacity. In contrast, the BSFC decreases with an increase in engine load as shown in **Figure 3**. A maximum of 56% reduction is evident in BSFC at full load capacity over minimum load value. Similar observations were reported by authors concluding the optimum value of engine load was approximately 52% using the same engine test setup

Table 7. Combustion parameters at full load for B0 and B20 blend ratio

Load (%)	Combustion parameters							
	CPP (bar)		HRR (J/CA)		ID (degree)		MRPR (bar/degree)	
	B0	B20	B0	B20	B0	B20	B0	B20
25	53.0	52.0	16.4	16.2	13.77	13.54	2.60	2.50
50	67.0	65.0	35.0	34.0.0	11.08	10.84	6.43	6.13
75	76.0	74.0	46.0	44.0	10.77	10.61	7.84	7.67
100	85.0	83.5	60.0	56.0	9.07	8.92	8.57	8.23

(Nanthagopal et al., 2018). Further, it is worthy to say that the efficiency and consumption of biofuel are not undesirably affected if the engine runs nearly at its full load capacity. During all the engine trials, thermo-physical properties were found responsible for the variation in engine performance between the diesel fuel and biodiesel fuel mixtures.

In this work, the CV of the biodiesel fuel possesses a higher value than diesel, which is the contrast as compared to previous studies (Algayyim & Wandel, 2022; Davidson et al., 2017; Tse et al., 2015; Ramalingam et al., 2018). To obtain optimum CV, pyrolysis might be a better option over conventional diesel fuel. Further, in the current study, the viscosity of the biodiesel is nearly 53% lower whereas it was nearly 44-96% higher than conventional diesel as stated in the literature. Therefore, in the present work, it seems that the viscosity will be a higher impacting parameter on the engine performance. It is also known that the mixing of the biodiesel fuel having a low viscosity improves atomization and vaporization. If the cone angle is kept wider than it harms the air-fuel ratio and combustion process in the engine as reported in previous literature (Rajak et al., 2019). Spray penetration optimization is reason for increasing SFCn and reduction in engine efficiency. The problem related to spray angle may be solved by tuning injector geometry and pressure accordingly.

Engine Combustion Characteristics

Combustion chamber pressure analysis is also an important tool to determine the behavior of CI engines, which directly affects performance. Cylinder test procedures are considered in the combustion chamber, such as maximum rate of pressure rise (MRPR), heat release rate (HRR), ignition delay (ID), and cylinder pressure. **Table 7** shows the general combustion parameters of a mixture of 100% B0 and B20.

Cylinder pressure analysis parameter

The rate of combustion depends on fuel involved in the premixed combustion phase is further affected by the peak pressure of the cylinder (Rajak & Verma, 2018). The diesel and eucalyptus biodiesel depict an engine loading at CR 17.5:1 with variation of the cylinder peak pressure at various engine loading conditions versus different blend ratios is shown in **Figure 6**. At B20, cylinder peak pressure compared with other blends ratio used in is found lesser than the B0 (pure diesel) by 1.76 % and B0 higher than B100 by 4.7% at CR 17.5.

Heat release rate cylinder

Due to the fuel mixing ratio, the heating rate of standard diesel is higher than that of biofuel-DF mixtures, which increases with the decrease of oil viscosity, thereby increasing

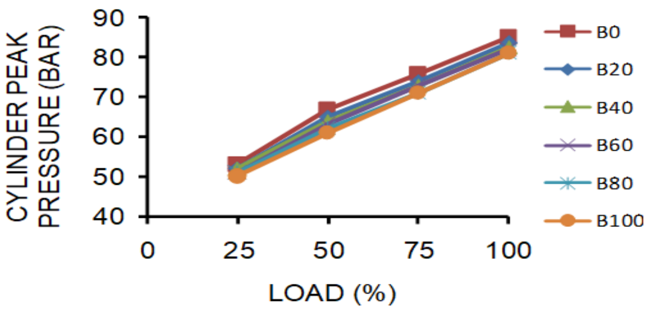

Figure 6. Cylinder peak pressure vs. load at 1,500 rpm (Source: Authors' own elaboration)

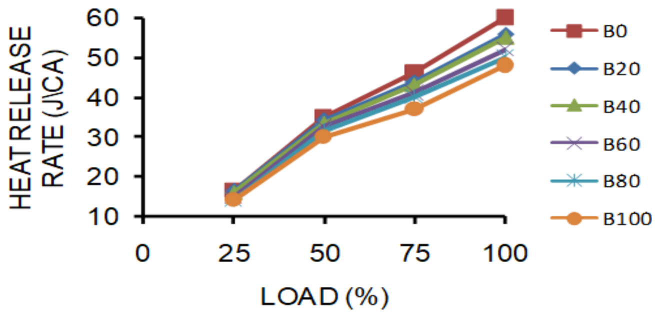

Figure 7. Heat release rate vs. load at 1,500 rpm (Source: Authors' own elaboration)

the injection speed. The heat release rate is affected by air inclusions and the lower mixing ratio of air and fuel, and the influence of fuel viscosity decreases with the increase of mixing ratio and oxygen content, which is higher than that of standard diesel (Prabhahar et al., 2012).

Due to the longer ignition delay and the higher heat release rate, the higher CV of diesel fuel increases the amount of fuel in the premixed combustion (Prabhahar et al., 2012). Under different engine load conditions (**Figure 7**) the heat release rate is 60 J/CA, 56 J/CA, 55 J/CA, 52 J/CA, 50 J/CA, and 48 J/CA, respectively for B0, B20, B40, B60, B80, and B100. The blends of B20 and B0 were found to be lower, about 6.6%, and the original CR was 17.5. In the case of a mixture, the value of the maximum heat release rate for B20 is 56 J/KW, which is close to diesel B0 (60 J/KW).

Maximum rate of pressure rises

The pressure in the first rising interval reaches a higher combustion pressure, which is called the peak pressure in the cylinder. In the second interval, as the crankshaft angle changes, it drops in a certain working cycle. The peak cylinder pressure appears near the top dead center, thereby increasing engine power output. The determination of knocking tendency and higher NO_X emissions directly depends on the MRPR in the combustion cylinder of the internal combustion engine (Mehta & Mehta, 2021; Sivaramakrishnan & Ravikumar, 2014).

Figure 8 shows the variation in the MRPR of a eucalyptus biodiesel blend under different engine load conditions. At 100% load, the MRPR (bar/degree) for B0 is 8.57, B20 is 8.23, B40 is 8.01, B60 is 7.5, B80 is 6.77, and B100 is 6.64.

For mixed ratios from B0 to B100, changes in MRPR under different engine load conditions were studied. The MRPR obtained for B0 is 3.96% higher than the MRPR for B20 fully

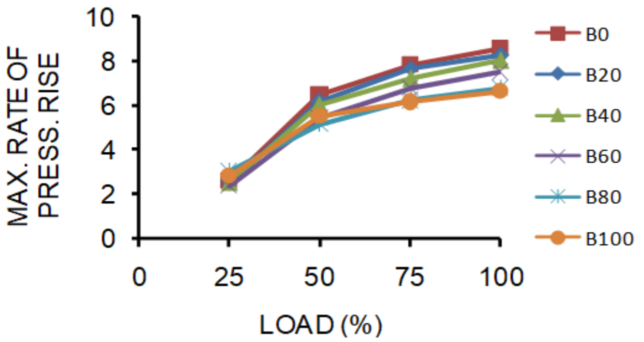

Figure 8. Maximum rate of pressure rise vs. load at 1,500 rpm (Source: Authors' own elaboration)

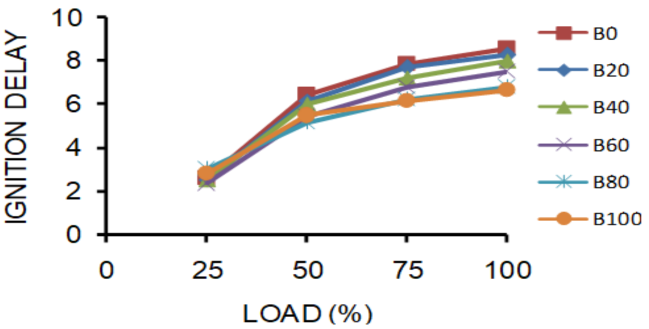

Figure 9. Ignition delay vs. load at 1,500 rpm (Source: Authors' own elaboration)

loaded using CR17.5. A significantly lower boost speed was achieved at 8.15 bar/degree.

It is considered to be within the allowable range of knocking, and the pressure increase rate when using B100 is lower than that of B0 with the same CR. Therefore, using the B100 with the same CR can be said to improve antiknock properties.

Ignition delay

Closed termination time is the time difference between the start of the crankshaft and the crankshaft flow start via the crankshaft rotation. Higher ignition times are associated with higher fuel starting times than additional ignition periods. Higher heat dissipation results in higher fuel efficiency, better performance, as well as higher engine output rates. The large delay in the blending of eucalyptus biodiesel indicates that the lean blend results in lower combustion temperatures and NOX emissions (Datta & Mandal, 2016).

Figure 9 shows that diesel and eucalyptus biodiesel contained in the CR 17.5 compound have different engine load and ignition delays. The CR is related to the ignition delay of diesel, biodiesel, and some of its compounds. For B0 and B100, heat dissipation decreased from 9.07 °C to 7.84 °C, and the combination of B20 and B80 decreased from 8.92 ° C to 7.84 °C and CR 17.5, respectively. This will increase the pressure of the compressed air and the temperature of the engine. It can stabilize the engine while maintaining the right temperature and pressure while producing a small amount of air.

The maximum rate of pressure rise concerning loads for all tested fuel blends is illustrated in **Figure 8** and cylinder peak pressure concerning load is shown in **Figure 6**. It is observed that the peak pressure values were lower with biodiesel and decrease significantly with an increase in blend ratio. Further, it is also observed that the maximum reduction in peak pressure is 60% at the B100 blend ratio. A similar trend is observed during the experiments with the lower heat release rate. Similar conclusions were also reported by authors (Rinaldini et al., 2016; Vihar et al., 2017) for biofuels produced using the pyrolysis approach. The low viscosity of the biodiesel and increasing blend ratios tend to inferior the fuel penetration and mixing of air-fuel ratio. As a result of which, the combustion process and heat release rate decrease. As per the results plotted in **Figure 7**, it is found that the heat release rate increases with an increase in engine load and decreases when we increase in blend ratio from B0 to B100.

Engine Emissions Characteristics

The exhaust gas parameters of the test engine using eucalyptus diesel and biodiesel as fuel are as follows: Emissions are divided into two categories: primary (hydrogen, carbon dioxide (CO_2), CO, sulfur dioxide, oxides of nitrogen, particles etc.) and secondary (sulfuric acid, ozone, peroxide nitrate etc.). In this study we calculated CO_2, NO_X, CO, HC, and fog emissions. The use of fossil fuels in the engine can lead to a variety of by-products, including HC, CO, NO_X, CO_2, soot, sulfur oxide, and dust in engine exhaust (Algayyim & Wandel, 2020). Many researchers are working to reduce harmful engine emissions. **Table 8** shows the emission parameters for the mixing ratio of B0 and B20 at 100% load.

Specific carbon dioxide emission

Figure 10 shows the change in specific emissions of CO_2 as a function of load. When using biofuels instead of fossil fuels as alternative fuels, lower the EGT, lower the premature combustion, and lower the heating value. Therefore, pre-ignition allows you to extend the time and angle of the crankshaft to complete an extension cycle. Therefore, the reason for the increase in CO_2 emissions when using biodiesel is that it takes longer time to convert CO into CO_2 when the engine uses biodiesel as fuel (Gashaw et al., 2015).

The higher mixing ratios of eucalyptus biodiesel increase the engine's CO_2 emissions. This forecast indicates that partial combustion is taking place in the engine compartment. It can be seen that the higher the engine load, lower the CO_2 emissions and the B20 blend ratio results are close to diesel.

Table 8. Summary of emission parameters at 100% load for B0 and B20 blend ratio

Load (%)	Emission parameters									
	CO_2 (g/KWh)		NO_X (g/KWh)		CO (g/KWh)		HC (g/KWh)		Smoke (%)	
	B0	B20	B0	B20	B0	B20	B0	B20	B0	B20
25	1,665.66	1,888.88	352.94	352.94	9.75	8.85	0.1840	0.1772	68.57	64.76
50	972.22	1,000.00	1,470.58	1,441.17	5.85	5.40	0.1181	0.0977	77.14	65.71
75	833.33	888.88	2,294.11	2,205.88	4.35	4.05	0.0863	0.0750	87.61	74.28
100	805.55	833.33	2,911.76	2,735.29	3.60	3.45	0.0568	0.0556	89.52	79.04

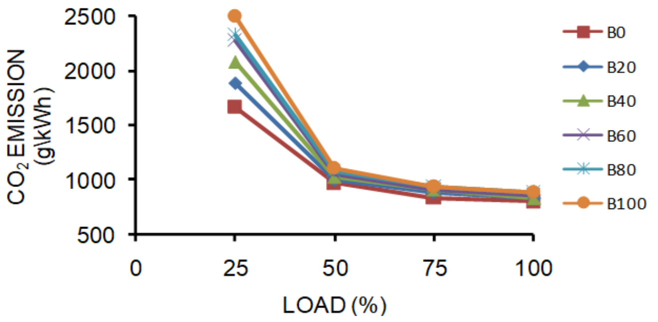

Figure 10. CO_2 emission vs. load at 1,500 rpm (Source: Authors' own elaboration)

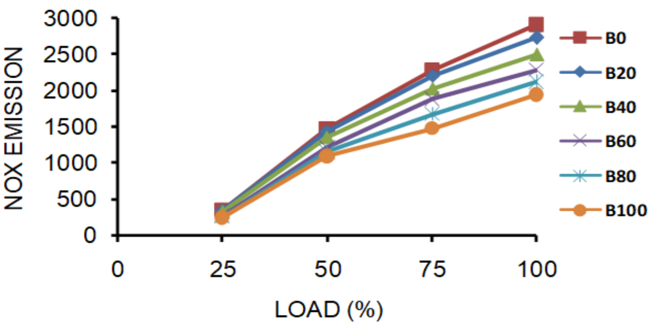

Figure 11. NO_X emissions vs. load at 1,500 rpm (Source: Authors' own elaboration)

Increasing the fuel mixture increases CO_2 emissions and improves the combustibility of the mixture. For CR 17.5, the CO_2 emissions of the B100 are 888.88 g/KWh and the B0 is 805.55 g/KWh. Compared to fully loaded diesel fuel, 20% biodiesel contains 3.44% more CO_2.

Fraction of NO_X emission in the exhaust gas

Figure 11 shows the NO_X formation of diesel and eucalyptus biodiesel, and their mixtures fluctuate with changes in engine load. NO_X emissions depend on the engine cylinder temperature, CR, oxygen content, and the time required for the reaction that consumes space during the combustion process. Due to the low temperature of the combustion chamber and low heat generation rate, NO_X emissions are low (Mathew & Anand, 2021; Wu et al., 2015). During the entire ignition period, the combustion chamber of the internal combustion engine contains nitrogen oxides and alternative toxic gases, and NO_X emissions are dependent on the temperature and pressure of the combustion chamber (Senthur et al., 2014).

Although it turns out that using biodiesel instead of diesel will lower the temperature of the exhaust gases. Experiments predict that NO_X emissions calculated with CR 17.5 will be lower than those of diesel. In CR 17.5, NO_X emissions at B0 is 2,911.76 PPM, B20 is 2,735.29 PPM, B40 is 2,500 PPM, B60 is 2,294 PPM, and B80 is 2,117 PPM, B100 is 1,941.17 PPM, which is lower than diesel with the same CR. Therefore, it is estimated that NO_X at CR 17.5 emissions will be reduced by 5.06%. This is the best B20 ratio to use eucalyptus biodiesel.

Hydrocarbon emission

Biodiesel has shown significant reductions in unburned HC emissions through improved combustion with a higher oxygen content using biodiesel and its blends compared to diesel fuel (Mohamed et al., 2020). HC emissions in exhaust gases decrease with increasing NO_X emissions (Murillo et al., 2007). Biodiesel and its diesel blend significantly reduce unburned HC emissions and increase NO and NO_X emissions compared to diesel fuel (Anand et al., 2011).

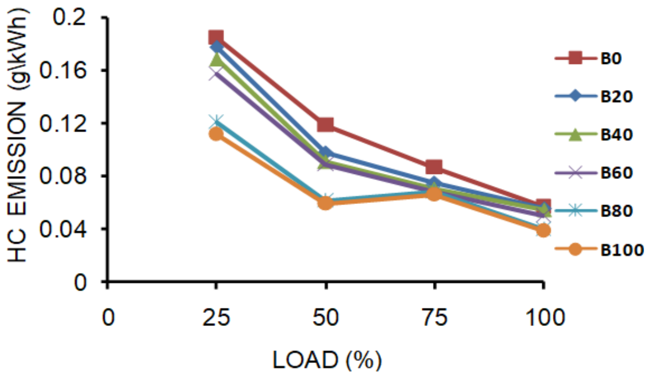

Figure 12. HC emissions vs. load at 1,500 rpm (Source: Authors' own elaboration)

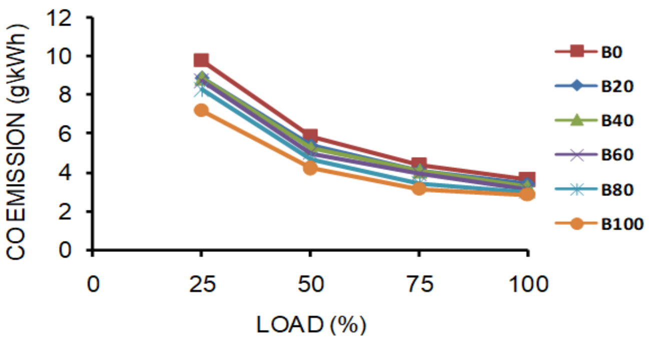

Figure 13. CO emissions vs. load at 1,500 rpm (Source: Authors' own elaboration)

Figure 12 shows the different loads and mixing ratios for measured HC emissions when using diesel and eucalyptus biodiesel. We found that eucalyptus biodiesel emits fewer HCs than diesel. The HC emissions calculated in the experiment are expected to be lower than pure diesel. At B0, the HC emission at CR 17.5 is 0.0568 g/KWh, B20 is 0.0556 g/KWh, B40 is 0.0545 g/KWh, and B60 is 0.05 g/KWh, B80 is 0.0397 g/KWh, and B100 is 0.0386 g/KWh, which is lower than a fully loaded diesel under the same CR. Therefore, at CR 17.5, B100 mixture ratio assumes that HC emissions are 32.04% lower than eucalyptus biodiesel emissions.

Carbon monoxide

Figure 13 shows the CO emissions of diesel and biodiesel from eucalyptus and their mixing ratio depending on engine load. The combustion process is caused by incomplete combustion of the engine (Singh et al., 2020). The presence of high oxygen molecules in the biodiesel chain during the conversion of biodiesel to CO_2 reduces CO emissions and production. CO emissions decrease with increasing engine load (Balat et al., 2009; Mathew & Anand, 2021). It has been found that the CO level when using biodiesel is lower than when using diesel fuel. Experiments predict that the calculated CO emissions are lower than pure diesel. CO emissions are at CR 17.5, B0 is 3.6 g/KWh, B20 is 3.45 g/KWh, B40 is 3.3 g/KWh, B60 is 3.15 g/KWh, B80 is 3.0 g/KWh, B100 is 2.85 g/KWh. Therefore, at CR 17.5, estimates that the CO emissions of the B20 blend are 4.16% lower than that of diesel using eucalyptus biodiesel.

Smoke emission

Due to the non-uniformity of the diesel combustion process, the fuel/air ratio in the combustion chamber cylinder has an important consideration. Smoke emissions are due to the fuel-air mixture being too thin to spontaneously ignite or support diffuse flames.

The fuel/air ratio requirement is too high for ignition (Balat et al., 2009). Increasing the oxygen content of biofuel/biodiesel reduces emissions and contributes to complete combustion (Arunkumar et al., 2019). **Figure 14** shows the relationship between flue gas fluctuations and different loads when using diesel fuel, as well as different mixing ratios of eucalyptus biodiesel and B100. It can be seen that the amount of smoke exhausted increases as the engine load increases, and the amount of smoke exhausted from B100 is smaller than that from B0. Compared to B0, we can see that the smoke emissions are 11.70% for B20 and 3.19% for B100. **Table 8** depicts a summary of emission parameters at 100% load for B0 and B20 blend ratios.

It is observed from **Figure 11** that, NO_X emission increases with an increase in engine load. The blend ratio is found effective in reducing NO_X emission at the higher capacity of engine load approximately above 25% of the full load. Similar observations were reported by other researchers in their studies (Nanthagopal et al., 2018; Rajak & Verma, 2018). Ignition delays are getting short due to high cetane numbers resulting in permitting more time to complete the combustion process consistently. Concerning the entire engine load, emission of CO decreases with an increase in blend ratios; see **Figure 13**.

Figure 12 shows the reduction in the HC emission, which is considered one of the important parameter of combustion efficiency at lower blend ratios. For higher blend ratios such as B60, B80, and B100, HC emission values are higher, which increases fuel consumption. This trend is completely contrary as compared to a previous study that was performed on a similar engine using biodiesel as a fuel (Nanthagopal et al., 2018). One another study also reported (Rajak et al., 2019) the opposite results in biodiesel using the transesterification method as compared to the pyrolysis approach. If the oxygen concentration is high with low viscosity in biodiesel, atomization and vaporization increase accordingly, this may be the reason for low CO emission.

Figure 14 shows the effect of blend ratios on smoke opacity as the engine load changes. As the blend ratio change from B0 to B100 at minimum engine load capacity, the smoke opacity also increases accordingly from 12% to 31%. On the other hand, at the maximum engine load, the smoke opacity increases from 17% to 38%. Similar results were found in (Attai et al., 2020; Mohamed et al., 2020) experimentation.

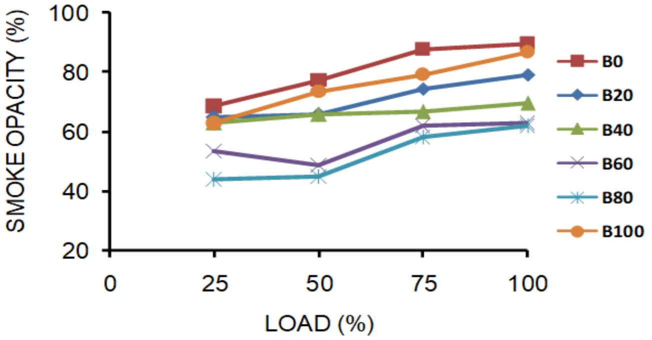

Figure 14. Smoke opacity (%) vs. load at 1,500 rpm (Source: Authors' own elaboration)

CONCLUSIONS

The current study has certainly highlighted some valuable results obtained from diesel engine tests fuelled with biodiesel derived from the biomass using pyrolysis as opposed to the transesterification process. From the experimental observations, even if the pyrolysis approach may not match the higher yield obtained from commercially proven transesterification processes, the biodiesel obtained in this way can result in higher CV and lower viscosity.

The biodiesel is having a cetane number of 54, the kinematic viscosity of 5.83 cSt, and a CV of 7,850 kcal/kg. The higher cetane number of the biodiesel resulted in a shorter ignition delay of biodiesel fuel blends, whereas the in-cylinder peak pressure, temperature, and heat release rate were lower as the biodiesel blend ratio increased progressively. Engine performance-related issues in terms of spray characterization may be challenging if the viscosity of the biodiesel is low. Though, it can be resolved by tuning the injector geometry and its pressure.

Using biodiesel derived from waste eucalyptus leaves in the CI engine, the following conclusions have been derived for a CR of 17.5 and 1,500 rpm:

1. At full load, the exhaust gas emission temperature is maximum, i.e., 587 K at B100.
2. At part load, NOx emission is minimum i.e., 235 ppm at B100.
3. HC emission is minimum i.e., 0.038 g/KW-hr at full load with B100.
4. The least CO emission is observed at full load with B100 i.e., 2.85 g/kW-hr.

In addition, we have observed a maximum of 50% reduction in NO_X without affecting the combustion efficiency of the engine. A high blend ratio above B40 adversely affects the thermal efficiency of the engine at a high value of engine load. HC and CO emissions were found to reduce with an increase in blend ratios. The variable parameters are blending ratio and engine load. The engine gives the best performance at B100 with the full load i.e., highest 33.57% BTE, 0.31 kg/KW-hr of lowest SFC, and minimum ignition delay.

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Declaration of interest: No conflict of interest is declared by the authors.

Ethical statement: The authors stated that are no human subjects were included in this study and informed consent was not applicable.

Data sharing statement: Data supporting the findings and conclusions are available upon request from corresponding author.

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