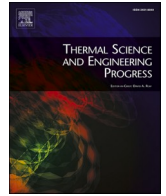




Contents lists available at ScienceDirect

Thermal Science and Engineering Progress

journal homepage: www.sciencedirect.com/journal/thermal-science-and-engineering-progress

Bio-based solutions for diesel engines: Investigating the effects of propolis additive and ethanol on performance and emissions

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ARTICLE INFO

Keywords:

Propolis
Ethanol
Diesel engine
Exhaust emissions
Engine performance

ABSTRACT

This study aimed to investigate the impact of the addition of ethanol and propolis into diesel fuel on the performance of a single-cylinder diesel engine, as well as the resulting exhaust emissions. To determine this, experiments were carried out with various fuel blends, including 100 % diesel, 95 % diesel blended with 5 % ethanol, 90 % diesel blended with 10 % ethanol, 95 % diesel blended with 5 % ethanol and propolis, and 90 % diesel blended with 10 % ethanol and propolis. The constituents of the propolis extract were analyzed with the gas chromatography-mass spectrometry technique. The experiments were carried out at a speed of 3000 RPM under various engine load situations, including unloaded and load conditions of 1.6, 3.2, 4.8, 6.4, 7.9, 9.5, and 11.1 N-meters. During the experimental trials, various parameters were measured, including the exhaust gas temperature, fuel line pressure, fuel consumption, exhaust emission, and in-cylinder pressure. Based on the collected data, the following parameters were evaluated: heat release rate; in-cylinder pressure; maximum pressure rise rate; cumulative heat release; exhaust gas temperature; brake-specific fuel consumption; thermal efficiency; and O₂, CO, CO₂, HC, NO_x, and PM emissions. Overall, the inclusion of propolis in diesel fuel was observed to decrease various key parameters, namely, the maximum pressure rise rate, cumulative heat release, thermal efficiency, heat release rate, and maximum in-cylinder pressure. Carbon monoxide, hydrocarbon, and particulate matter emissions decreased, but carbon dioxide emissions underwent an increase. The addition of propolis resulted in an increase in brake-specific fuel consumption.

1. Introduction

According to the report of the International Organization of Motor Vehicle Manufacturers, the total number of vehicles in 2021 had increased by 235.52 % in comparison to that in 1999. Moreover, these numbers are increasing day by day [1]. In addition, according to the 2021 report of the European Automobile Manufacturers Association, 10.5 % of the vehicles sold throughout 2020 were electric, 11.9 % were hybrid, and 47.5 % were petrol-powered vehicles. The percentage of vehicles using diesel as fuel was 28 % [2]. This shows that diesel-fueled vehicles still occupy a high share of the automobile market. They are popular because of their high compression ratio and high thermal efficiency. However, the increase in the number of diesel engines day by

day has increased diesel fuel consumption and almost caused the depletion of fossil fuel resources. The high nitrogen oxide and soot emissions that diesel engines release have a significant negative impact on the environment. Some researchers have stated that oxygen-rich alcohols are effective on exhaust emissions [3]. Others have also shown that the addition of oxygen to diesel fuel also has a reducing effect on CO, HC, NO_x, and PM emissions from engine exhausts [4].

Numerous domestic and global endeavors and regulatory measures, exemplified by the Paris Agreement [5], the European Green Deal [6], and an extensive body of over 2200 associated legislations and policies [7], are oriented toward the mitigation of greenhouse gas emissions [8]. The study conducted by Nguyen et al. [9] involved the manufacturing of biodiesel using waste from palm oil production, which was later evaluated in a diesel engine. Research findings indicate that the cetane

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<https://doi.org/10.1016/j.tsep.2024.102421>

Received 12 October 2023; Received in revised form 19 January 2024; Accepted 20 January 2024

Available online 26 January 2024

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Nomenclature	
BSFC	Brake-specific fuel consumption
BTDC	Before top dead center
CA	crank angle degree
CAD	Crank angle degree
CAS	Chemical Abstracts Service
CO	Carbonmonoksida
CO ₂	Carbondioksida
D	Diesel
DE10	%90 diesel + %10 Ethanol
DE5	%95 diesel + %5 Ethanol
DP10	%90 diesel + %10 propolis
DP5	%95 diesel + %5 propolis
FID	Fréchet inception distance
GC-MS	Gas Chromatography Mass Spectrometry
HC	Hydrocarbon
J	Joule
MPa	Mega Pascal
MPRR	Maximum pressure rise rate
Nm	Newton meter
NO _x	Nitrogenoksida
O ₂	Oxygen
PM	Particulate matter
RCCI	Reactivity controlled compression ignition
RPM	Revolutions per Minute

number of biodiesel derived from palm oil is 30 % more than that of regular diesel fuel. Hence, it has been observed that palm biodiesel exhibits a higher propensity for self-ignition than regular diesel fuel. Yoon et al. [10] examined changes in combustion and exhaust emissions of ultra-low sulfur diesel and biodiesel in an indirect injection diesel engine. The combustion properties of diesel and biodiesel exhibited comparable tendencies, as evidenced by empirical observations. Biodiesel exhibited a lower ignition delay time under all conditions in comparison to ultra-low sulfur diesel, owing to its elevated cetane number. In scenarios of reduced load, biodiesel exhibited decreased brake thermal efficiency, as well as reduced hydrocarbon and carbon monoxide emissions. However, nitrogen oxide emissions were consistently greater across all load circumstances. Yilmaz et al. [11] employed the response surface methodology in their study to identify the most favorable fuel combinations for a diesel engine—specifically, diesel, pentanol, and biodiesel derived from waste oil. The researchers discovered that the optimal blend, characterized by a high R2 ratio, consisted of 79.09 % diesel, 8.33 % biodiesel, and 12.58 % pentanol. Furthermore, Yilmaz et al. [12] examined the impact of incorporating 35 % n-butanol, n-propanol, and n-butanol alcohols into diesel and biodiesel fuels on engine performance and emissions. The incorporation of n-butanol led to a reduction in harmful emissions. Temizer et al. [13] conducted a numerical investigation using simulation software to examine the effects of incorporating ethanol and diethyl ether into diesel fuel. An augmentation in nitrogen oxide emissions was seen upon the introduction of ethanol, accompanied by an enhancement in turbulent kinetic energy. Firat et al. [14] investigated the impact of ethanol and diesel fuels on engine performance and emissions when utilized in dual direct injection and RCCI modes, in comparison to normal diesel fuel. The RCCI mode exhibited a higher level of thermal efficiency in comparison to the dual direct injection system. The dual direct injection system demonstrated enhanced reduction of CO and HC emissions. The researchers successfully enhanced the reduction of NO_x and smoke emissions in both dual direct injection and RCCI modes. The study conducted by Tripatara et al. [15] focused on biodiesel research. The researchers noted a drop in the heat release rate as a result of the elevated cetane number of biodiesel and a reduction in smoke density with an augmented proportion of biodiesel in the mixture. Lapuerta et al. [16] focused on the modeling of fuel mixtures derived from the combination of diesel and biodiesel fuels with varying concentrations of butanol and ethanol. Their study revealed a negative correlation between the alcohol content and the viscosity of the mixtures. Uyaroglu et al. [17] examined the impact of incorporating biodiesel and organic manganese into diesel fuel on engine performance and emissions. The incorporation of biodiesel and organic manganese resulted in a notable enhancement in thermal efficiency of the engine. Simultaneously, the utilization of biodiesel resulted in an escalation of fuel consumption. Zhan et al. [18] and Geng et al. [19] achieved the production of a low-viscosity and low-density blend by introducing ethanol into biodiesel fuel. According to their statement,

spraying enhanced the atomization of this mixture.

Ethanol is characterized by a high oxygen content and a low cetane number. Therefore, the introduction of ethanol into biodiesel increases the ignition delay time [20]. Enhanced combustion is attained by extending the premixing duration, which influences the oxygen level within the biodiesel-ethanol blend. The initiation of combustion is postponed until the proper moment. Tse et al. [21] investigated the particle emissions of diesel, biodiesel, and ethanol mixtures. The researchers noted that the introduction of ethanol into diesel and biodiesel resulted in a significant decrease in the quantity of particulate matter. During combustion, which was characterized by a notably elevated temperature of approximately 1400 °C, the robust triple bond present in nitrogen molecules inside the fuel underwent dissociation. Consequently, nitrogen combined with oxygen in the form of free radicals, leading to the formation of thermal NO_x structures. The rapid synthesis of NO_x in hydrocarbon flames is attributed to the formation of free radicals within the flame front, as described by this mechanism [22]. In fuel, NO_x is formed as a product of the reaction between the nitrogen and oxygen attached to the fuel during combustion. Free radical formation during combustion determines the reaction rate and rapid NO_x production. A free radical is a highly reactive molecule with one or more unpaired electrons [23]. The National Renewable Energy Laboratory states that antioxidant studies that prevent the formation of free radicals increase to eliminate the negative effect of NO_x [24]. Antioxidants, which have oxygen-scavenging properties, prevent the initiation or progression of oxidation reactions since oxidation reactions result in free radicals. For example, when the antioxidant level in the human body is insufficient, large amounts of free radicals form in the body, adversely affecting human health [25]. Similar to this adverse effect on human health, excess free radicals negatively affect fuel performance. Free radicals are unstable molecules that carry unpaired electrons in atomic orbitals [26]. The antioxidant effect reduces the formation of free radicals, eliminating their negative effects. Antioxidants reduce free radicals with four effects: scavenging effect, quencher effect, chain breaking effect, and repair effect [27]. To produce propolis, bees collect a sticky substance from tree resins and combine it with enzymes in their mouths [28]. Propolis is used to close cracks and gaps and treat bee pests in the hive [29]. Therefore, the most crucial factor in the preference for propolis is its known antioxidant properties [30].

Besides the summaries of some studies reviewed in the introduction, Table 1 shows the effects of some selected publications on emissions. All these studies agree that the addition of oxygen-rich additives in fuel is effective on emissions. It is now accepted that the addition of oxygen-rich nanoparticles in fuel to reduce emissions, which researchers have emphasized in recent years, also affects engine power.

Notably, the chemicals used in studies focusing on the addition of oxygen-rich nanoparticle additives in fuel are not obtained from biological sources, which can increase environmental pollution. Considering the production processes of these additives, it can be predicted that

Table 1

Title	Year	Results
Synthesis, Characterization and Application of SnO ₂ @rGO Nanocomposite for Selective Catalytic Reduction of Exhaust Emission in Internal Combustion Engines [31]	2023	NOx ↓ HC ↓ CO
Investigation of the effect of carbon nanotube addition to diesel-biodiesel blend on engine performance and exhaust emissions [32]	2023	NOx ↑ HC ↓ CO ↓ Soot
Utilization of multiwalled carbon nanotubes (MWCNT) additive in HCCE engine to widen operating range [33]	2023	HC ↓ CO
γ-Al ₂ O ₃ supported silver nanoparticle applied in C ₃ H ₈ -SCR: Nanosphere and nanoflake [34]	2023	NOx ↑
Evaluation of karanja and safflower biodiesel on engine's performance and emission characteristics along with nanoparticles in DI engine [35]	2023	NOx ↓ CO ↓ Soot
The effects of metallic fuel addition into canola oil biodiesel on combustion, engine performance and exhaust emissions [36]	2023	NOx ↑ HC ↓ CO ↑ Soot
Towards nationwide implementation of 40% biodiesel blend fuel in Indonesia: a comprehensive road test and laboratory evaluation [37]	2023	NOx ↑ HC ↓ CO ↓ Soot

they may pollute the environment. Therefore, it is critical that the fuel additives be of biological origin. This line of thought is being explored in the current study for the first time in this field. For this purpose, propolis was chosen as an additive in the current study. Propolis has a high oxygen-holding capacity. At the same time, it can be dissolved in ethanol in nano sizes and mixed with fuel. Propolis dissolved in ethanol was added to diesel fuel as an additive in this study, and its effects on emissions were investigated.

The researchers conducted a series of controlled experiments using various concentrations of the ethanol-propolis blend to systematically evaluate its effect on engine operation. The study aimed to provide valuable information on the potential benefits and feasibility of using propolis-blended ethanol as an additive in diesel fuel.

2. Materials and method

2.1. Test fuels

The processes of obtaining the test fuels are shown schematically in Fig. 1. The CAS number of the ethanol solvent used in the preparation of the propolis extraction was 64–17–5. Raw propolis, which was extracted in ethanol, was obtained from the province of Bingöl, Türkiye. The raw propolis was kept in the deep freezer at $-20\text{ }^{\circ}\text{C}$ for 4 h. Then, the particle size of the raw propolis was minimized in the grinder. Seles brand industrial grinder was used for the grinding process. The obtained milled propolis was added to 96 % ethanol at a ratio of 1:10 (w/v) and mixed in a magnetic stirrer at 500 RPM, $35\text{ }^{\circ}\text{C}$, for 24 h. The Denver Instrument SI-234 equipment was utilized for weighing the products throughout the creation of the solutions. Additionally, the Isolab I.613.01.001 magnetic stirrer was employed for effectively mixing the solutions. Following the combination of the solutions, the resulting mixtures underwent filtration using Whatman No:1 filter paper, with the subsequent removal of the insoluble residue located at the bottom. The remaining clear solution was kept in a vacuum oven at $40\text{ }^{\circ}\text{C}$ for 48 h to evaporate the solvent from the solution, and thus, the propolis extract was produced from crude propolis. Propolis-ethanol solutions were formed by adding 10 % (w/v) of the propolis extract formed in this experiment process into 500 ml ethanol. These solutions were again filtered through filter paper, and propolis-ethanol samples were produced as clear solutions.

A GC–MS analysis was performed to determine the components of the produced propolis extract. In the analysis, Agilent brand GC–MS and FID detector were used simultaneously. The brand of the column used in this analysis was BPx90, and the column dimensions were 100 mm x 0.25 mm x 0.25 μm . Helium gas adjusted to 1 ml/min flow rate was used as column carrier gas. The samples were analyzed under

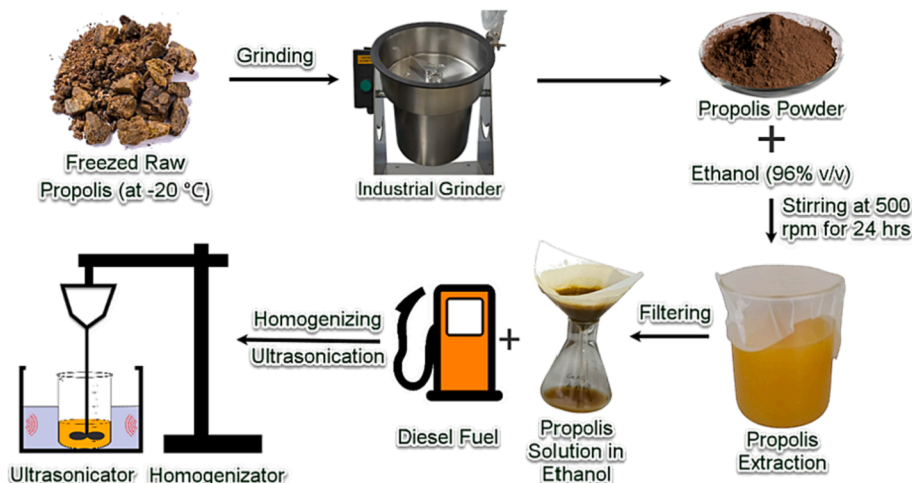


Fig. 1. Production process of test fuels.

chromatographic conditions by providing a certain temperature rise per minute. The libraries in the device were used to determine the MS results. The clear solution formed after the filtration of propolis into the ethanol extract was used in the GC–MS analysis. The following processes were then carried out:

- From the clear solution, 100 μL was drawn into the syringe, and 10 ml of hexane was added and vortexed.
- Then, 100 μL of 2 N KOH was added to the propolis extract-hexane solution and vortexed.
- The resulting solution was centrifuged at 4500 RPM for 10 min.
- The clear solution remaining on the top of the samples after the centrifugation was taken into vials and placed in the GC–MS device for analysis.

The fuels used during the experiments were obtained from companies selling commercially. Some of their properties are listed in Table 2.

Some technical specifications of the prepared mixtures are listed in Table 3.

2.2. Experimental test setup

A single-cylinder, four-stroke, air-cooled, direct-injection diesel engine was used in the experiments. The fuel line and in-cylinder pressure values of the engine were measured by sensors. The technical specifications of the engine used in the experiments are shown in Table 4.

The experiments were done with five different fuel mixtures: D, DE5, DE10, DP5, and DP10. In-cylinder pressure values were measured with a Kistler 6052C brand piezoresistive air-cooled sensor, and fuel line pressure values were measured with an Oprand OPTD. 32288GPA brand air-cooled sensor. The position of the crankshaft was determined with the FNC optical crank encoder. K-type thermocouples were used for measuring exhaust gas temperature. Fuel consumption was measured in mass with a precision balance. A Bosch BEA350 brand gas analyzer was used for measuring exhaust emission values. Device measurement ranges and uncertainties are shown in Table 5.

The engine test setup schematic view is shown in Fig. 2.

The experimental studies were conducted at 3000 RPM (a constant engine speed) with both no load and 1.6, 3.2, 4.8, 6.4, 7.9, 9.5, and 11.1 Nm engine loads. In-cylinder pressures were measured with data recording at a resolution of 0.5 CAD, and the results were processed by taking a pressure average for every 100 cycles. An analytical model for calculating heat release rate employs the first law of thermodynamics and the ideal gas equation. The following equation calculates the heat release rate per crank angle using cylinder volume and in-cylinder pressure values.

$$\frac{dQ_n}{d\theta} = \frac{\gamma}{\gamma - 1} P \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dP}{d\theta} \quad (1)$$

In Eq. (1), $dQ/d\theta$ represents the net heat release rate in joules per kelvin per square meter (J/CAD), θ denotes the CAD, V represents the specific heat rate, V signifies the cylinder capacity in m^3 , and P denotes the cylinder pressure in bars. In-cylinder pressure data were recorded with a resolution of 0.5°CA. The Kline McClintock approach [38] was

Table 2
Physical and chemical properties of diesel and biodiesel.

Fuel Properties	Diesel	Ethanol
Kinematics viscosity (mm^2/s), at 40°C	3.4	1.36
Density (g/cm^3) at 15 °C	0.834	0.79
Lower heating value (kJ/kg)	43,010	29,300
Latent heat of evaporation (kJ/kg)	270–301	840
Flashpoint (°C)	66	11
Cetan number	59.5	6
Oxygen (% w)	0	%34.78

Table 3
Some properties of test fuels and blends.

Properties	D	DE5	DE10	DP5	DP10
Kinematics viscosity (mm^2/s), at 40°C	3.4	3.22	3.38	4	3.38
Density (g/cm^3) at 15 °C	0.83	0.825	0.82	0.826	0.824
Lower heating value (kJ/kg)	42,440	41,500	40,800	41,200	40,100

Table 4
Test engine technical specifications.

Engine	Four strokes, direct injection, air-cooled and naturally aspirated
Model	186 FAG
Cylinders Number	1
Intake system	Naturally aspirated
Compression ratio	18:1
Stroke \times Bore	70 \times 86 mm
Engine power (Maximum)	7 kW (3600 RPM)
Displacement volume	406 cm^3
Pressure of injection	19.6 \pm 0.49 Mpa
Fuel delivery advance angle	21 (°CA) BTDC

Table 5
Used in experiment exhaust emissions device technical properties.

Measurement	Measuring Range	Resolution	Precision
CO (% vol)	0–10	0.01	± 1 %
CO ₂ (% vol)	0–20	0.01	± 0.5 %
HC (ppm)	0–20000	1	± 12
Smoke opacity (%)	0–20	0.01	± 2

employed to compute total data uncertainties gathered in studies. Table 6 provides information regarding the precision of the measuring instruments and the computed overall uncertainties.

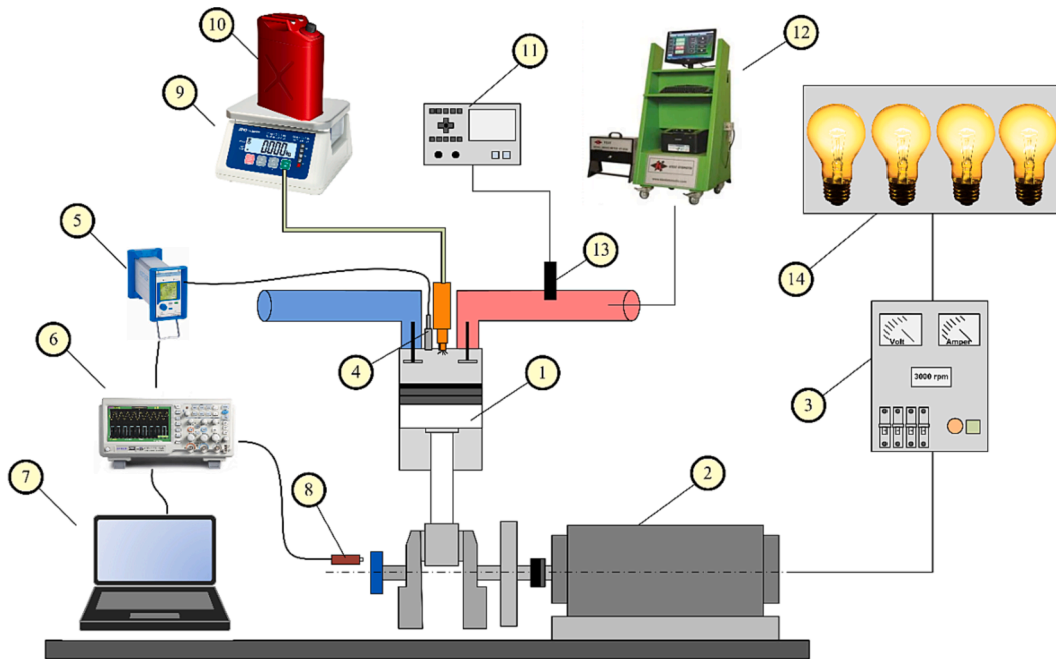
3. Results and discussion

The GC–MS analysis result graph obtained by characterizing the ethanol extract of propolis in determining the content analysis is presented in Fig. 3, and the qualitative and quantitative analysis results of the content of the propolis extract are listed in Table 7. When the GC–MS results were examined, phenolic compounds; fatty acids; high-carbon organic groups (alkanes, alkenes, aldehydes, and ketones); and amine groups were found in the propolis extract, with fatty acids having the highest proportion. The component with the highest percentage among fatty acids was palmitic acid [39]. The percentage ratio of all fatty acids in the sample was determined as 95.81 % [40]. Fatty acids are known to have high levels of antioxidant properties [41]. Phenolic compounds [42] and high-carbon compounds also have antioxidant properties [43]. These results demonstrate that the addition of propolis to fuel provides an advantage to the fuel due to the high antioxidant levels in the propolis samples and the oxygen-holding capacity of antioxidant materials.

3.1. Effect of ethanol-propolis additive on in-cylinder pressure

For the in-cylinder pressure values, the highest engine torque value of 11.1 Nm engine load values have been analyzed and presented in the discussion section.

Fig. 4 shows the torque value of 11.1 Nm and the in-cylinder pressure values varying with crank angle for various fuel combinations. The highest in-cylinder pressure recorded was 43.17 bar, determined by the use of diesel fuel. The minimum in-cylinder pressure was 42.74 bar



1) Diesel engine, 2) Generator, 3) Generator control panel, 4) Cylinder pressure sensor, 5) Charge amplifier, 6) Oscilloscope, 7) Computer, 8) Crank encoder, 9) Precision scale, 10) Fuel tank, 11) Data logger, 12) Exhaust gas analyzer, 13) K-type thermocouple, 14) Lamp load unit

Fig. 2. Experimental test setup.

Table 6
Uncertainties and measuring device.

Measured parameter	Measurement device	Accuracy
Engine speed	Incremental encoder, RPM	±1%
Cylinder pressure	Pressure sensor, bar	±0.5 %
Fuel line pressure	Pressure sensor, bar	±1%
Fuel mass	Precision scale, g	±0.1 %
Exhaust gas temperature	Thermocouple, °C	±1%
Time measurement	Digital chronometer, s	±1%
Calculated results	Uncertainly value	
Power	±1.17 %	
BSFC	±1.54 %	

while using a DP5 fuel blend under a torque of 11.1 Nm. The highest in-cylinder pressure value was observed at a crank angle of 5 degrees after the top dead center for all fuel combinations. Under typical conditions, the inclusion of ethanol in diesel fuel would be expected to affect the ignition delay. However, contrary to expectations, no such effect was observed. The addition of ethanol to diesel fuel caused a drop in maximum pressure. The addition of ethanol caused a decrease in the maximum in-cylinder pressure due to its low calorific value. Also, the addition of propolis caused a marginal decrease in the maximum in-cylinder pressure. The calorific value of fuels plays a very important role in determining the pressure generated during combustion in internal combustion engines [43]. According to the findings of many studies, fuels with higher calorific values show better combustion performance. Therefore, in-cylinder pressure values are expected to decrease [44].

In oxygen-rich fuel mixtures added to fuels, researchers state that the calorific values of fuels can have negative effects on combustion parameters due to uneven combustion. In particular, it is stated that a low calorific value partially delays combustion and affects the combustion time. Experimental results have shown that the inclusion of propolis in the ethanol blend leads to a more pronounced decrease in pressure compared to the fuel combination without propolis additive, and

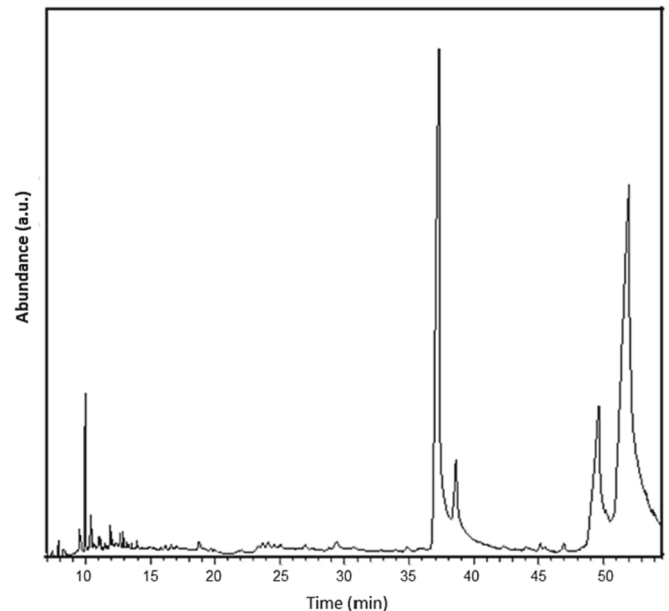


Fig. 3. GC-MS graph of propolis-ethanol extraction.

although the increased amount of oxygen in the fuel blends increases the combustion of the fuel, the calorific value is more influential in the results [45].

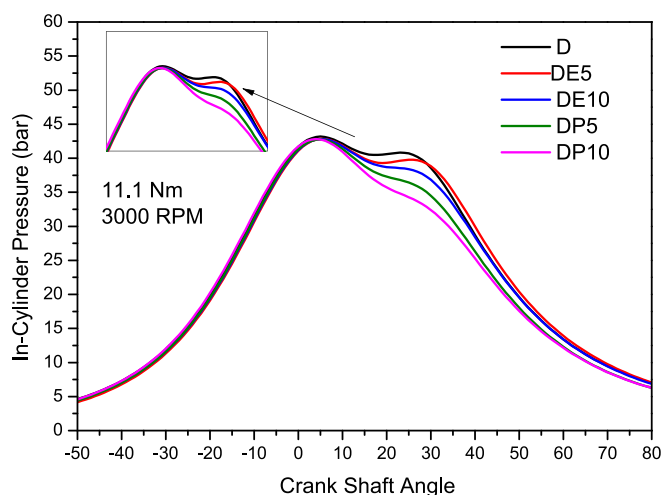
3.2. Effect of ethanol-propolis additive on heat release value

The variation of the heat release rate calculation for the torque value of 11.1 Nm for four different fuel mixtures and diesel fuel depending on CAD is presented in Fig. 5. It was seen that there is a similar situation to the in-cylinder pressure in heat release rates. It was observed that the

Table 7

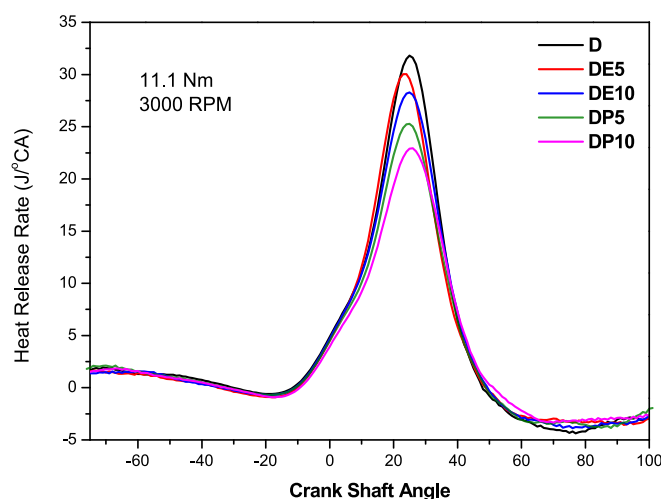
Chemical composition of propolis-ethanol extraction from GC-MS analysis.

Time	Area%	Library/ID.	Structure Type	CAS Number	Qual
7.87	0.22	3-[4-(4-methoxy-phenyl)-thiazolyl]-8-methyl-2,3,3A,4,5,6-hexahydro-1H-pyrazino[3,2,1-JK]carbazole-2-	Phenolic compounds	2000808-27-0	86
9.95	1.79	Methyl-5-amino-2-[(3-chlorophenyl)amino]-1,3-oxazole-4-carboxylate	Phenolic compounds	2000421-61-5	95
10.36	0.38	N-((E)-[4-(dimethylamino)phenyl]methylidene)-2-phenyl-2H-1,2,3-benzotriazol-5-amine	Phenolic compounds	299928-54-4	83
10.43	0.31	3-Formyl-N-methyl-9-[phenylethynyl]dibenzo[2,3-a:5,6-a'](1,4)-thiazine	Phenolic compounds	2000652-79-5	72
11.12	0.25	2-(6-Ethoxy-4-methyl-quinazolin-2-ylamino)-5-methyl-pyrimidine-4,6-diol	Amin groups	351469-03-9	86
11.51	0.16	2-chloro-4-[cyano(methoxy)(phenyl)methyl]-N-[cyano(phenyl)methylene]aniline-N-Oxide	Phenolic compounds	2000785-26-3	78
11.90	0.31	Oxime-,methoxy-phenyl-	Phenolic compounds	2000074-65-0	87
12.89	0.14	5(6H)-Quinazolinone,7-(2-furanyl)-7,8-dihydro-2-[(6-methoxy-4-methyl-2-quinazoliny)amino]-	Amin groups	2000785-52-8	91
22.05	0.10	Cyclohexadecane	Higher alkanes	000295-65-8	92
23.71	1.88	Stearic acid	Fatty acids	000112-61-8	96
24.63	0.10	Ethyl-9hexadecenoate	Fatty acids	054546-22-4	52
25.10	0.14	Linolelaidic Acid	Fatty acids	002566-97-4	94
27.02	0.08	(9E)-9-ICOSENE	Higher alkenes	074685-29-3	95
29.33	0.11	2-Methyl-Z,Z-3,13-octadecadienol	Higher alcohols	2000467-28-3	91
29.44	0.09	Myristic acid	Fatty acids	000544-63-8	80
37.29	32.53	Palmitic acid	Fatty acids	000057-10-3	99
38.60	4.17	Palmitoleic acid	Fatty acids	000373-49-9	99
46.98	0.29	9-Octadecenal,(Z)-	Higher aldehydes	002423-10-1	93
48.52	0.05	26-Nor-5-cholesten-3beta-ol-25-one	Ketones	007494-34-0	93
49.68	14.62	1-Heptadecanecarboxylic-acid	Fatty acids	000057-11-4	99
51.69	19.11	Elaidic acid	Fatty acids	000112-79-8	99
51.83	23.02	Oleic Acid	Fatty acids	000112-80-1	99
53.90	0.15	cis-Vaccenic acid	Fatty acids	000506-17-2	99

**Fig. 4.** In-cylinder pressure changing with the crank angle for 11.1 Nm torque value and different fuel mixtures.

heat release rate decreased with the addition of ethanol and further decreased with the addition of propolis. The highest heat release rate was obtained with diesel fuel with $31.8 \text{ J}^\circ\text{CA}$ at 25 CAD. The lowest was $22.9 \text{ J}^\circ\text{CA}$ at 26 CAD for the DP10 fuel mixture. The obtained values suggest that the maximum heat release rate value decreased with the addition of ethanol. It decreased even more with the addition of ethanol mixed with propolis. The maximum heat release rate of DP10 fuel had decreased by 27.98 % in comparison to the maximum heat release rate of diesel fuel.

In studies on biologically based fuel additives, researchers have mentioned that the catalyst properties of additives are effective on emissions but reduce engine performance values. This is explained by their flammability properties. In this study, it is thought that the additive adversely affects the combustibility of the additive and thus causes a decrease in the heat release rate, but despite the decrease in the calorific value, the amount of oxygen in the fuel additive partially improves the combustion and prevents the decrease to some extent [46].

**Fig. 5.** Heat release rate changing with the crank angle for 11.1 Nm torque value and different fuel mixtures.

3.3. Effect of ethanol-propolis additive on cumulative heat rate

The variation of the cumulative heat release calculation for 11.1 Nm torque for four different mixtures and diesel fuel depending on the CAD is presented in Fig. 6. A similar situation occurred with in-cylinder pressure in cumulative heat release. Ethanol addition decreased cumulative heat release, while propolis addition decreased it further. The highest cumulative heat release value was obtained in diesel fuel with 718.18 J at 48 CAD. The lowest was 604.84 J at 51 CAD for DP10 fuel mixture. These values show that the cumulative heat release value decreased with the addition of ethanol and decreased even more with the addition of ethanol mixed with propolis. The maximum cumulative heat release rate of DP10 fuel decreased by 15.78 % compared to diesel fuel.

This can be explained, as mentioned in the previous section, by the low calorific value of ethanol, the partial deterioration of the atomization of the fuel mixture, the tendency of propolis not to burn, and the decrease in thermal value. Similar to the studies carried out, the statements support the results of the study [47].

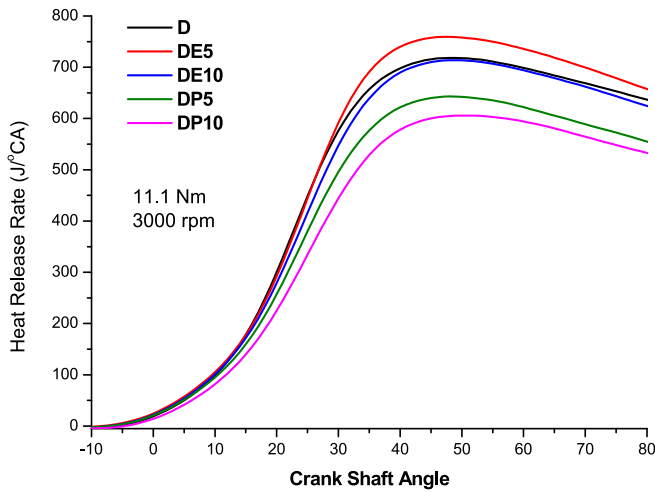


Fig. 6. Cumulative heat release changing with the crank angle for 11.1 Nm torque value and different fuel mixtures.

3.4. The effect of ethanol-propolis additive on the rate of pressure increase

The variation of the calculation of the maximum in-cylinder pressure increase rate depending on the crank angle at a torque value of 11.1 Nm for four different mixtures and diesel fuel is present in Fig. 7. When MPRR was examined, no change was observed in any of the fuel mixtures in the compression period. After the top dead center, that is, during combustion, a situation similar to that with the in-cylinder pressure occurred. MPRR decreased with the addition of ethanol and further decreased with propolis addition. The highest MPRR value was obtained in diesel fuel with 1.09 MPa at 38 CAD. The lowest was 0.83 MPa at 41 CAD for DP10 fuel. Thus, adding ethanol to fuel decreased the maximum pressure increase rate value, and the rate decreased even more with the addition of ethanol mixed with propolis. The maximum heat release rate of DP10 fuel was 23.85 % compared to diesel fuel. This is because, as stated in the previous section, the lower calorific value of ethanol is low, and the addition of propolis reduces the calorific value more [48].

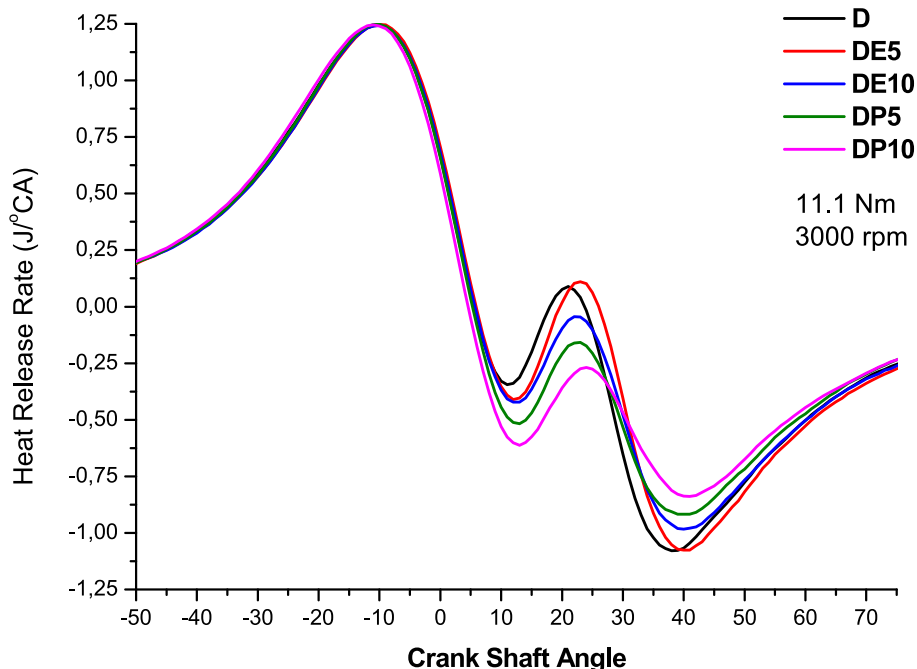


Fig. 7. Maximum Pressure Rise Rate changing with the crank angle for 11.1 Nm torque value and different fuel mixtures.

3.5. The effect of ethanol-propolis additive on CO emissions

The CO emission-torque changing of the test fuels can be seen in Fig. 8. When the graph is analyzed with respect to torque, it becomes evident that the maximum carbon monoxide emission value among all torque values, while maintaining a constant engine speed of 3000 RPM, was seen with conventional diesel fuel. CO emissions decreased when the torque value at which the trials were conducted increased. The recorded minimum CO concentration was 0.04 ppm when utilizing DP10 fuel and operating at a torque of 11.1 Nm. In trials conducted under conditions of constant engine speed, it is hypothesized that the observed reduction in CO emissions across all fuel combinations, as torque increased, can be attributed to the enhancement of combustion resulting from the concurrent rise in thermal efficiency. A notable rise in thermal efficiency, exhaust temperatures, and NO_x emissions, accompanied by a concurrent decrease in CO emissions, was observed in the current scenario. This observation is substantiated by graphical representations that demonstrate a declining trend in HC emissions and specific fuel usage.

When the graph is analyzed with respect to fuel, it becomes evident that the tests conducted with regular diesel fuel exhibited the greatest levels of CO emissions for each load situation. However, the introduction of ethanol and propolis into the standard diesel fuel led to a reduction in CO emissions. The experiments conducted using DP10 fuel exhibited the lowest recorded levels of CO emissions. The observed trend indicates a decrease in CO emissions with an increase in the ethanol and propolis content within the mixture, regardless of the torque values. In the no-load test conducted using normal diesel fuel, the maximum recorded figure for CO emissions was 0.28 ppm. The recorded minimum CO emission level was 0.04 ppm when the torque was set at 11.1 Nm using a fuel combination consisting of DP10. The CO emissions of the DP10 fuel mixture decreased by 32.14 % under no-load conditions as compared to that in diesel fuel. When torque tests with a magnitude of 11.1 Nm were analyzed, it was observed that the emission of CO in the DP10 fuel combination exhibited a reduction of 63.63 %. This reduction was found to be the most significant when compared to the emissions of diesel fuel. The addition of ethanol to fuel is believed to decrease CO emissions across various load conditions. This is attributed to the increased thermal efficiency resulting from the oxygen content of ethanol, which

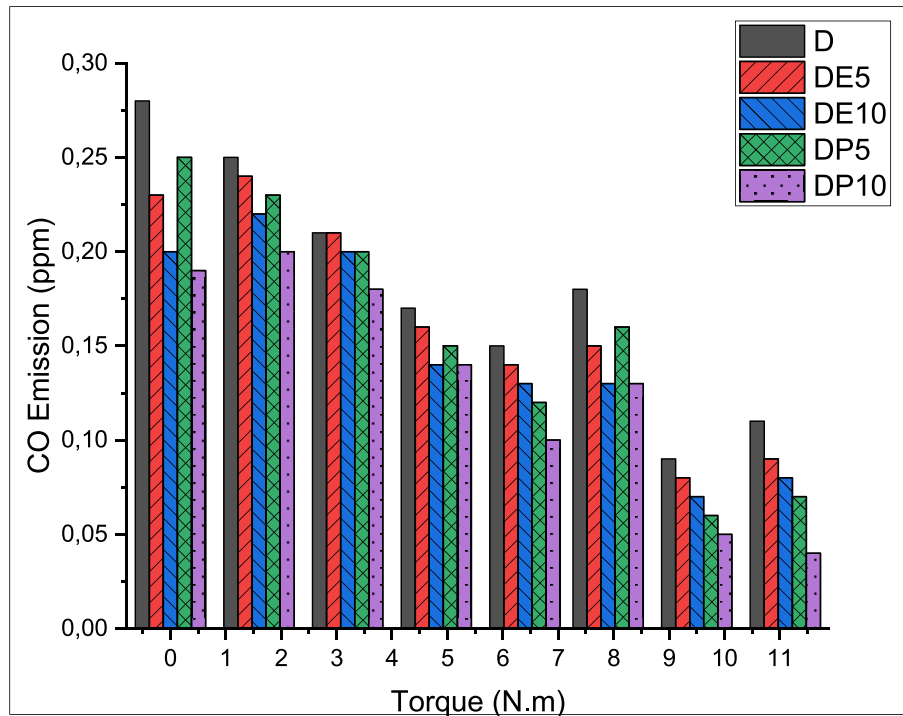


Fig. 8. CO emissions change with torque for diesel, diesel-ethanol, and diesel-propolis fuel mixture.

facilitates more efficient burning. The inclusion of propolis is believed to result in a decrease in CO emissions across all load conditions. This is attributed to the antioxidant characteristics of propolis, which enable it to interact with unstable free radicals in the surrounding environment and convert oxygen. This assertion is supported by previous studies [45]. The addition of propolis to diesel is believed to enhance the stable oxygen content within the combustion chamber due to the oxygen-converting properties of propolis. Consequently, this augmentation

facilitates more efficient combustion compared to the utilization of standard diesel fuel[49].

3.6. The effect of ethanol-propolis additive on CO₂ emissions

Fig. 9 shows the variations in CO₂ emissions with varied torque values and fuel compositions. When the data pertaining to torque is analyzed, it becomes evident that the DP10 fuel mixture yielded the

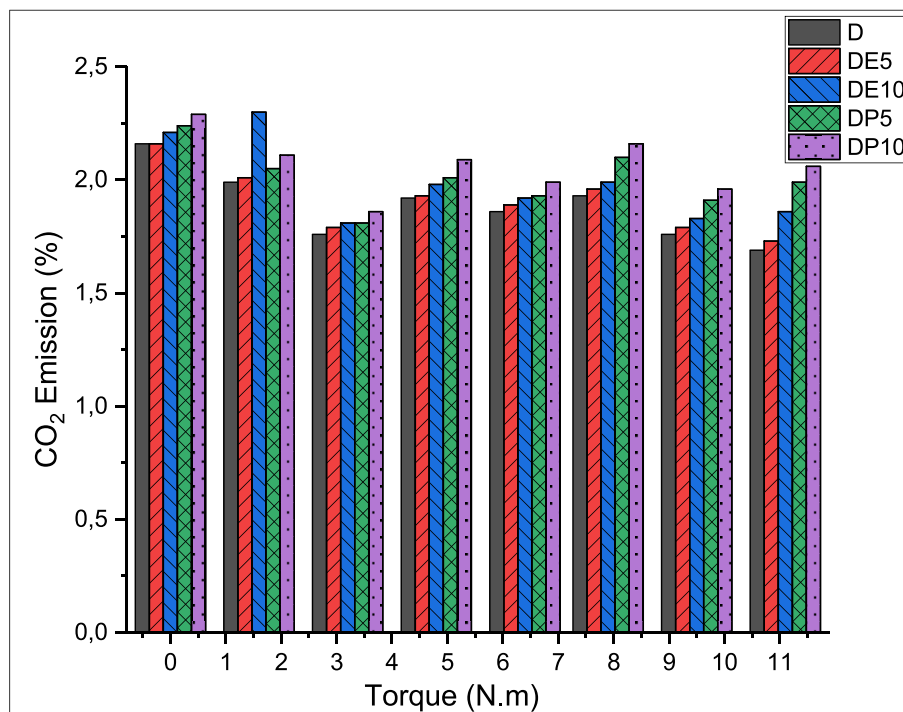


Fig. 9. CO₂ emissions change with torque for diesel, diesel-ethanol, and diesel-propolis fuel mixture.

highest recorded CO₂ emission value among all torque values at a consistent speed of 3000 RPM. The CO₂ emissions exhibited a reduction at first and then stabilized at consistent levels as the torque value increased. The minimum recorded CO₂ emission was 1.76 % when utilizing regular diesel fuel at torque levels of 3.2 Nm and 9.5 Nm. In trials conducted under conditions of constant engine speed, it is hypothesized that the observed reduction in CO₂ emissions across all fuel combinations, as torque increased, can be attributed to enhanced combustion resulting from improved thermal efficiency. The observed phenomenon entails a positive correlation between the rise in thermal efficiency, exhaust gas temperatures, and NO_x emissions and the concurrent decrease in CO₂ emissions. This correlation is substantiated by graphical representations illustrating a declining pattern in HC emissions, CO emissions, and specific fuel usage.

The CO₂ readings recorded for each load condition exhibited their greatest levels when DP10 diesel was utilized. The introduction of ethanol and propolis into diesel fuel resulted in an increase in CO₂ emissions. The tests conducted using regular diesel fuel yielded the lowest recorded CO₂ values. The CO₂ emission demonstrates a positive correlation with the ethanol and propolis ratio in the mixture across all torque values. The CO₂ emission reached its peak at 2.29 % during the no-load situation when DP10 fuel was utilized. The minimum recorded CO₂ emission value was 1.76 % at a torque of 3.2 Nm when diesel fuel was used. Additionally, when the DP10 fuel was utilized, the CO₂ emission increased by 6.02 % in comparison to diesel fuel under no-load conditions. The CO₂ emissions evaluated exhibited a significant rise of 21.89 % while DP10 diesel was utilized, which represents the largest disparity in comparison to diesel fuel in terms of torque, specifically that of 11.1 Nm. The prevailing belief is that the inclusion of ethanol in fuel leads to an increase in CO₂ emissions across all load conditions. This is attributed to the enhanced thermal efficiency resulting from the oxygen content of ethanol, which facilitates more efficient combustion. Additionally, it possesses the capacity to undergo a chemical reaction that results in the conversion of oxygen. The addition of propolis to diesel is believed to enhance the stable oxygen content within the combustion chamber due to its oxygen-converting properties. Consequently, this leads to improved combustion when compared to the utilization of regular diesel fuel [50].

3.7. The effect of ethanol-propolis additive on PM emissions

Fig. 10 illustrates the relationship between PM emissions and torque for various fuel combinations. The experiments conducted using diesel

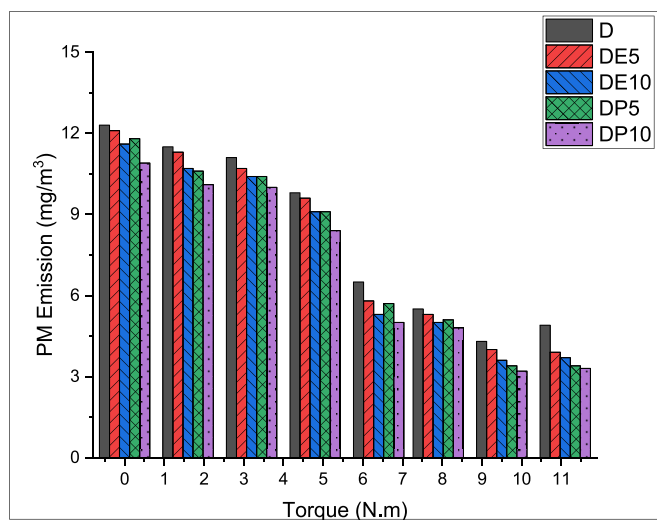


Fig. 10. PM emissions change with torque for diesel, diesel-ethanol, and diesel-propolis fuel mixture.

fuel yielded the highest recorded figure for PM emissions. An increase in torque value corresponded to a decrease in PM emissions. In experimental trials including DP10 fuel at a torque of 9.5 Nm, the recorded PM concentration reached its minimum value of 3.2 mg/m³. The observed phenomenon of reduced PM emissions in various fuel blends as torque increased, irrespective of the fuel type employed in the conducted experiments at a consistent engine speed, is attributed to the enhanced combustion process resulting in improved thermal efficiency. In instances where PM emissions underwent a reduction, a corresponding rise was observed in thermal efficiency, exhaust temperatures, and NO_x emissions. Conversely, HC emissions and specific fuel consumption tended to decline. This observation substantiates the declining pattern of PM emissions.

The maximum PM value for each load scenario was determined using diesel fuel. The incorporation of ethanol and propolis into diesel fuel resulted in a reduction in PM emissions. The DP10 fuel exhibited the lowest recorded PM value. The observation indicates that PM emissions decreased as the ratio of ethanol to propolis increased in the mixture, regardless of the torque values. In the no-load test conducted using normal diesel fuel, the recorded PM emission value reached its peak at 12.3 mg/m³. The minimum PM emission value observed was 3.2 mg/m³ when the engine was operating at a torque of 9.5 Nm and using a fuel mixture with a diesel particulate filter level of 10 (referred to as DP10). The DP10 fuel exhibited a reduction of 11.38 % in PM emissions compared to that of traditional diesel fuel under no-load conditions. The fuel mixture of DP10 resulted in a reduction of 32.65 % in PM emissions, exhibiting the most significant difference when compared to diesel fuel. The addition of ethanol to fuel is believed to decrease PM emissions across various load conditions. This is attributed to the reduction in diesel content resulting from the inclusion of ethanol, which enhances thermal efficiency due to its oxygen content. This makes the combustion even more efficient. The incorporation of propolis into the system results in a decrease in PM emissions across various load situations, mostly due to the additive's antioxidant capabilities. It is widely believed that this substance possesses the capacity to undergo a chemical reaction with unstable free radicals present in the surrounding environment, facilitating the conversion of oxygen. The inclusion of propolis in the fuel results in an enhanced capacity for oxygen conversion, leading to an increase in the stable oxygen content within the combustion chamber. It is postulated that under these circumstances, the combustion process is enhanced in comparison to the conditions observed when employing ordinary diesel fuel [51].

3.8. The effect of ethanol-propolis additive on NO_x emissions

Fig. 11 illustrates the changes in NO_x emissions and torque for various fuel combinations. When the data is analyzed in relation to torque, it becomes evident that diesel fuel yields the highest NO_x emission across all torque values at an engine speed of 3000 RPM. A positive correlation was often observed between torque and NO_x emission, whereby an increase in torque led to an increase in NO_x emission. The experiment conducted with a DP 10 fuel at 1.6 Nm torque yielded the lowest recorded NO_x emission of 89 ppm. The observed phenomenon of NO_x emission increasing in all fuel combinations as torque increased, irrespective of the specific fuel type employed in the conducted trials at a consistent engine speed, is believed to be attributed to the enhancement in combustion resulting from the rise in thermal efficiency. Whenever NO_x emissions increased, a corresponding inclination toward an increase was observed in thermal efficiency and exhaust temperatures. Simultaneously, the graphs representing HC, CO, PM emissions, and specific fuel consumption tended to exhibit a reduction.

When the graphical representation of fuel emissions was analyzed, it became evident that diesel fuel exhibited the greatest levels of NO_x emissions across various loads. However, the introduction of ethanol and propolis as additives demonstrated a notable reduction in NO_x emissions. The fuel mixture that yielded the lowest emission of NO_x was

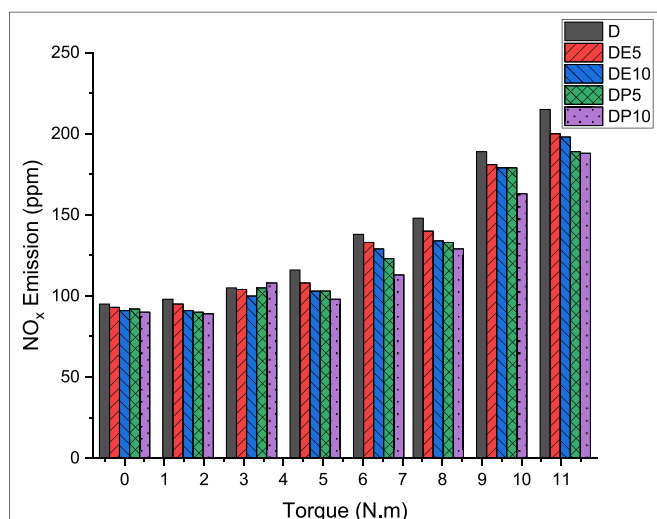


Fig. 11. NO_x emissions change with torque for diesel, diesel-ethanol, and diesel-propolis fuel mixture.

determined to be DP10. NO_x emissions decreased with a rise in the ethanol and propolis ratio in the mixture across all torque values. The maximum level of NO_x emissions recorded was 215 ppm with the application of 11.1 Nm of torque using diesel fuel. The recorded minimum level of NO_x emissions was 89 ppm at a flow rate of 1.6 Nm using DP10 fuel.

When the no-load situations were examined, it was observed that the NO_x emissions, as determined in the test involving DP10 fuel, exhibited a reduction of 4.21 % in comparison to that in diesel fuel. Upon analysis of the tests conducted at a torque of 11.1 Nm, it was found that the emission of NO_x, as measured using DP10 fuel in diesel engine testing, exhibited a reduction of 7.9 %. The addition of ethanol to fuel in various load conditions is believed to decrease NO_x emissions. This is attributed to the enhanced thermal efficiency resulting from the presence of oxygen in the ethanol, which facilitates more efficient combustion. The use of propolis as a means to mitigate NO_x emissions across various load conditions is believed to stem from its capacity to interact with unstable free radicals in the surrounding environment through oxygen transformation, owing to its inherent antioxidant capabilities. Including propolis in the fuel enhances the stable oxygen content within the combustion chamber, resulting in improved combustion as compared to that in conventional diesel fuel conditions [52].

3.9. The effect of ethanol-propolis additive on BSFC

The graph displayed in Fig. 12 illustrates the relationship between BSFC and torque for various fuel combinations. When the torque-related graph is analyzed, it becomes evident that the tests conducted at a consistent speed of 3000 RPM yielded the highest BSFC value across all torque values when DP10 fuel was employed. The observed trend indicates that BSFC decreased as the torque value in the experimental setup increased. The test conducted with regular diesel fuel at a torque of 11.1 Nm yielded the lowest recorded BSFC value of 603 g/kWh. The observed phenomenon of a drop in BSFC value across all fuel combinations as torque increased, irrespective of the fuel type, is attributed to the enhancement of combustion and subsequent improvement in thermal efficiency. In instances where the BSFC number underwent a decline, a concurrent pattern of rising thermal efficiency, exhaust temperatures, and NO_x emissions was observed. This observation aligns with graphical representations that demonstrate a declining trend in HC and CO emissions, as well as specific fuel consumption.

The analysis of the graph with respect to the fuel mixture makes it evident that the DP10 fuel exhibited the greatest BSFC values across all

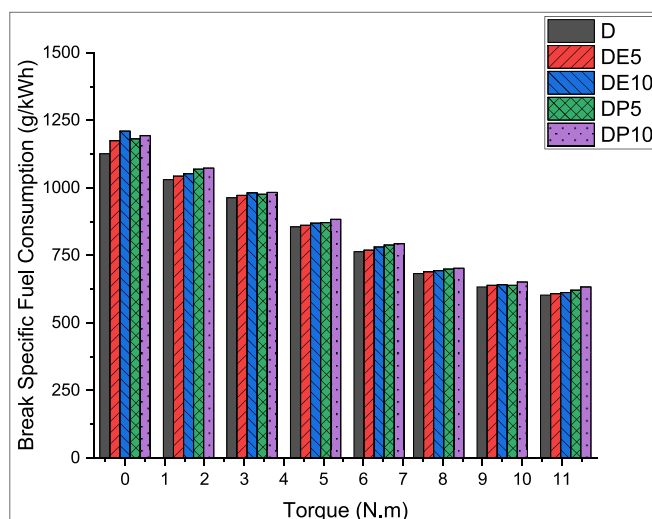


Fig. 12. BSFC change with torque for diesel, diesel-ethanol, and diesel-propolis fuel mixture.

load conditions. The addition of ethanol and propolis to the diesel fuel increased BSFC. The diesel fuel exhibited the lowest BSFC values as determined by the measurements. The observed trend indicates that a positive correlation exists between the ethanol and propolis ratio in the mixture and the BSFC value across all torque values. The maximum BSFC figure observed was 1073 g/kWh when using DP10 fuel at a torque of 1.6 Nm. The minimum BSFC figure observed was 603 g/kWh at a torque of 11.1 Nm when using diesel fuel. In the absence of a load, the DP10 fuel exhibited a 5.95 % increase in BSFC compared to that of the diesel fuel. The DP10 fuel exhibited a 4.96 % increase in BSFC when subjected to a torque of 11.1 Nm, compared to that in the diesel fuel. The addition of ethanol to diesel fuel leads to an increase in the BSFC value across all load conditions. This can be attributed to the reduction in the diesel ratio within the fuel composition. The presence of ethanol enhances the thermal efficiency of the fuel due to its oxygen content, resulting in more efficient combustion. The observed phenomenon of propolis enhancing the BSFC value across various load situations is believed to be attributed to its antioxidative capabilities, enabling it to react with unstable free radicals in the surrounding environment and facilitate the conversion of oxygen. Adding propolis to fuel is hypothesized to enhance the stable oxygen content within the combustion chamber. This is attributed to propolis oxygen conversion capability, resulting in improved combustion compared to ordinary diesel fuel [53].

3.10. The effect of ethanol-propolis additive on thermal efficiency

Fig. 13 illustrates the relationship between thermal efficiency and torque for various fuel blends. When the graph is analyzed with respect to torque, it becomes evident that the diesel fuel exhibited the highest thermal efficiency value among all torque values at a consistent speed of 3000 RPM. A positive correlation was observed between torque and thermal efficiency, whereby an increase in torque resulted in an increase in thermal efficiency. The recorded thermal efficiency value in the no-load state using DP10 fuel was 12.8 %. In trials conducted under conditions of constant engine speed, it is postulated that the observed enhancement in thermal efficiency across all fuel combinations, irrespective of fuel type, with increasing torque can be attributed to the amelioration of combustion processes. The observed phenomenon involves a rise in exhaust temperatures and NO_x emissions, coinciding with an upward trend in thermal efficiency. This correlation is substantiated by graphical representations illustrating a simultaneous decline in HC, CO, and PM emissions, as well as brake-specific fuel consumption.

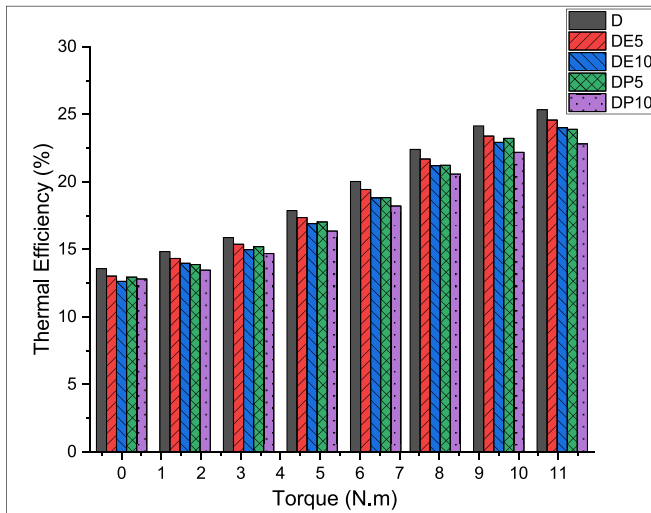


Fig. 13. Thermal efficiency change with torque for diesel, diesel-ethanol, and diesel-propolis fuel mixture.

When the graph is analyzed with respect to fuel, it becomes evident that diesel fuel yielded the maximum thermal efficiency values for each load state. However, the addition of ethanol and propolis to the diesel fuel resulted in a decrease in thermal efficiency. The experimental results indicate that the DP10 fuel had the lowest thermal efficiency. The observed trend indicates a decrease in thermal efficiency as the proportion of ethanol and propolis in the combination increased, across all torque values. The maximum thermal efficiency achieved was 25.3 % when a torque of 11.1 was applied using diesel fuel. In the absence of any external load, the thermal efficiency of the system was observed to be 12.8 % when utilizing DP10 fuel. In the absence of a load, it was seen that the thermal efficiency, as determined in the experiment utilizing DP10 fuel, exhibited a reduction of 5.62 % in comparison to that when the diesel fuel was utilized. The analysis of the tests conducted using a torque value of 11.1 Nm showed that the thermal efficiency of DP10 fuel exhibited a reduction of 9.99 % in comparison to that of diesel fuel.

The addition of ethanol-propolis fuel additive in diesel fuel leads to a decrease in thermal efficiency under all load conditions due to a decrease in the total energy output after combustion. A possible explanation for this situation is the effect on the atomization of fuel mixtures and the thermal value. Despite the amount of oxygen in the fuel mixtures, it is believed that the decrease in thermal value and the resistance of propolis to combustion are effective in reducing efficiency. Similar results in additives of biological origin also indicate that resistance to combustion with thermal value has an effect on thermal efficiency [54].

3.11. The effect of ethanol-propolis additive on O_2

Fig. 14 shows the relationship between O_2 emission and torque for various fuel mixtures. The DP10 fuel measured the torque with the maximum O_2 value at a constant 3000 RPM speed. The experiment's torque value and O_2 levels did not vary significantly. With diesel fuel and 7.9 Nm of torque, the lowest O_2 value recorded was 17.9 %. The reason the O_2 value stayed constant in all fuel combinations even when the torque increased was that despite the difference in torque, all tests were conducted at the same engine speed. Therefore, no discernible change occurred to the air volume entering the cylinder.

The tests utilizing DP10 fuel produced the highest O_2 values for each load condition, and the addition of ethanol and propolis to regular diesel fuel boosted the O_2 value, according to an analysis of the graph in terms of fuel. The tests carried out with regular diesel fuel exhibited the lowest O_2 values. The O_2 value increased as the mixture's ethanol and propolis ratios rose for all torque values. The test with the highest O_2 value,

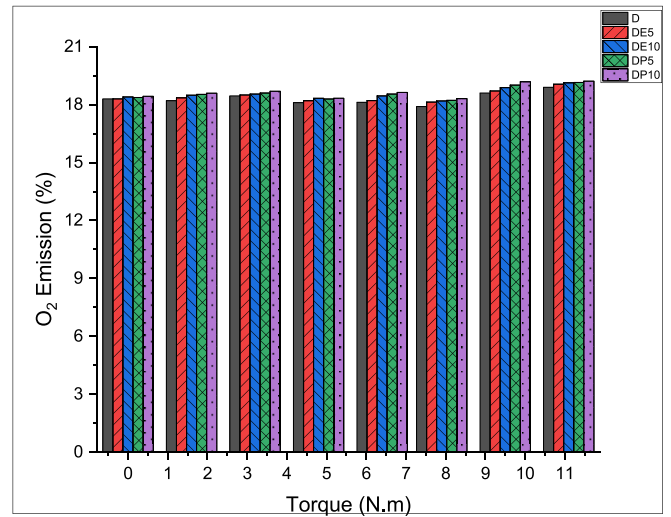


Fig. 14. O_2 emissions change with torque for diesel, diesel-ethanol, and diesel-propolis fuel mixture.

measured 19.21 % at 11.1 Nm load, was conducted with DP10 fuel. The lowest O_2 value in the testing with pure diesel fuel was 17.9 % at 7.9 Nm of torque. The O_2 value recorded in the test with DP10 fuel rose by 0.71 % in the no-load condition as compared to that in the diesel fuel. An examination of the tests with a torque value of 11.1 Nm revealed that the O_2 value recorded in the test with DP10 fuel rose by 1.64 % in comparison to the tests carried out with diesel fuel. Because of the reduction in the diesel ratio in the fuel mixture and the oxygen in the ethanol supplied to the fuel, it is believed that adding ethanol to diesel fuel raises the O_2 value at every load [55].

The ability of propolis to convert oxygen by reacting with unstable free radicals in the environment as a result of its antioxidant capabilities is assumed to be the cause of its ability to boost the O_2 value at all load circumstances. Due to this ability, adding propolis to the fuel raises the stable oxygen concentration in the combustion chamber [56].

3.12. The effect of ethanol-propolis additive on O_2

Fig. 15 displays the variations in HC emissions and torque across different diesel mixtures. Diesel fuel had the highest recorded HC emission value, regardless of the torque levels. HC emission decreased

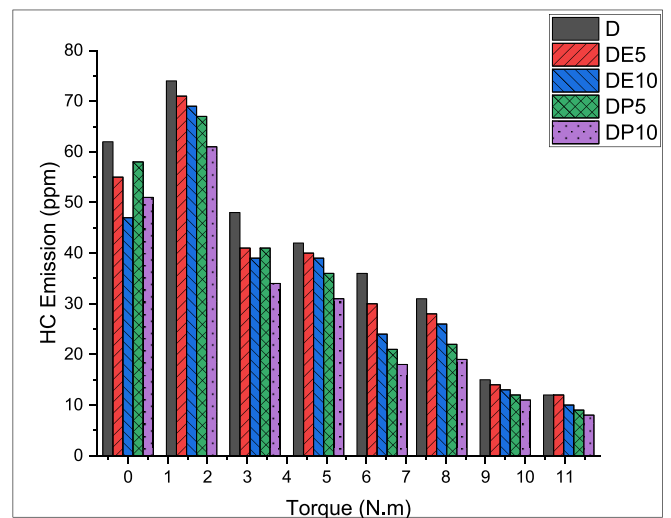


Fig. 15. HC emissions change with torque for diesel, diesel-ethanol, and diesel-propolis fuel mixture.

when the torque value was increased. The reported minimum HC emission level was 8 ppm, achieved with DP 10 fuel and 11.1 Nm of torque. The HC emissions exhibited a decrease across all diesel blends as the torque increased, irrespective of the specific fuel composition utilized. The reason for this phenomenon might be the enhancement of combustion processes resulting in increased thermal efficiency. The increase in thermal efficiency, exhaust gas temperatures, and reduction in NO_x emissions collectively contributed to circumstances that led to a decrease in HC emissions. Moreover, it facilitated the mitigation of carbon monoxide emissions and the conservation of fuel resources, particularly in relation to braking mechanisms. The experimental investigation revealed a reduction of 33.33 % in the HC emission mixture of the DP10 fuel blend as compared to that in diesel fuel. This observation was made during torque testing, with an applied torque of 11.1 Nm. The addition of ethanol to diesel fuel is hypothesized to reduce HC emissions across various load circumstances due to the enhanced thermal efficiency of the fuel resulting from the presence of oxygen. This improved combustion efficiency enables more effective utilization of the fuel. Propolis exhibits antioxidant capabilities and effectively mitigates HC emissions across various load situations by engaging in a chemical reaction with unstable free radicals in the surrounding environment, facilitating the conversion of oxygen. The addition of propolis to fuel enhances combustion efficiency, in comparison to that of conventional diesel fuel, by augmenting the stable oxygen content within the combustion chamber, owing to its oxygen-converting properties [57].

3.13. The effect of ethanol-propolis additive on exhaust gas temperature

Fig. 16 demonstrates the correlation between exhaust gas temperature and torque across different fuel mixtures. When evaluated at a consistent speed of 3000 RPM, diesel fuel had the highest exhaust gas temperature among all torque values. An increase in torque was generally accompanied by a rise in exhaust gas temperature. Under conditions of no load, the DP 10 fuel mixture yielded exhaust gas temperatures that reached a minimum of 223 degrees Celsius. Irrespective of the specific fuel composition employed, it is widely posited that the increase in exhaust gas temperature, observed across all diesel blends, is mostly attributed to enhanced combustion as torque levels escalated. In the present scenario, the increase in thermal efficiency and NO_x emissions aligned with the observed pattern of escalating exhaust gas temperatures. The aforementioned tendency was further substantiated by the observed decrease in levels of HC, CO, PM, and fuel consumption specifically related to vehicle braking.

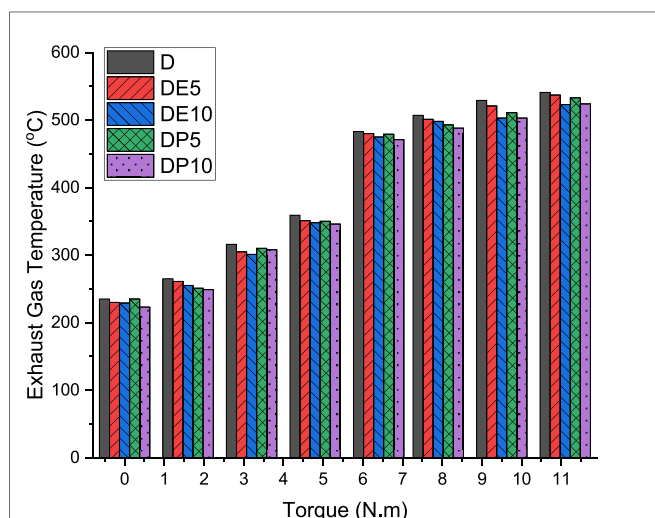


Fig. 16. Exhaust gas temperature change with torque for diesel, diesel-ethanol, and diesel-propolis fuel mixture.

When the graph was analyzed in relation to fuel, it was observed that the highest recorded exhaust gas temperature was obtained using diesel fuel for each load situation. The addition of ethanol and propolis to diesel fuel resulted in a reduction in the temperature of its exhaust gas. The DP10 fuel mixture exhibited the lowest recorded exhaust gas temperature. Across all levels of torque, an increase in the proportion of ethanol and propolis in the mixture resulted in a decrease in the temperature of the exhaust gas. The highest recorded exhaust gas temperature and torque for diesel fuel were 541 °C and 11.1 Nm, respectively. Under no-load conditions, the lowest exhaust gas temperature recorded for DP10 diesel was 223 °C. The exhaust gas temperature of the DP10 fuel mixture decreased by 5.11 percent under no-load conditions, in comparison to that of diesel fuel. At an applied torque of 11.1 Nm, the DP10 fuel mixture exhibited a reduction in exhaust gas temperature by 3.14 % as compared to that of diesel fuel. The addition of ethanol to diesel fuel resulted in a notable decrease in its heating value compared to pure diesel fuel. As a consequence, the exhaust gas temperature decreased under various load conditions, leading to a decrease in the overall energy output at the completion of combustion [58]. The thermal efficiency decreased at all load settings when propolis was added to the fuel due to its lower heating value compared to diesel fuel, which is similar to ethanol, and its ability to decrease the amount of energy released during combustion [59].

The exhaust gas temperature is an indicator of combustion in the cylinder. Sometimes, excessive prolongation of the fuel combustion time causes the exhaust gas temperature to increase. A possible explanation for this is that the fuel additive tends to not burn [61]. In the current study, a more accurate interpretation would be to explain the tendency to decrease of the exhaust gas temperature by the falling thermal value, as there have been decreases in the intra-cylinder pressure and heat dissipation rates. Despite the falling thermal value, it is believed that the oxygen in the additive mitigates the decrease in exhaust gas temperature.

4. Conclusions and future perspectives

In this study, experiments were carried out to determine the effects of the addition of propolis dissolved in ethanol to diesel fuel on exhaust emissions and engine performance for a single-cylinder diesel engine. The following outcomes were attained.

- **Combustion characteristics:** The addition of ethanol resulted in a decrease in the maximum pressure increase rate, heat release rate, cumulative heat release, and in-cylinder pressure. The inclusion of propolis intensified this declining tendency. The addition of ethanol and propolis caused the combustion to advance while increasing the in-cylinder pressure and ignition delay.
- When ethanol was blended into diesel fuel, CO emissions were greatly reduced while CO₂ emissions increased. It might be claimed that increasing the amount of oxygen-rich (ethanol) fuel results in a decrease in CO emissions and an increase in CO₂ emissions. Additionally, the addition of propolis dissolved in ethanol to diesel resulted in an increase in CO₂ emissions and a further drop in CO emissions. Because of its antioxidant properties, propolis can be said to provide greater CO₂ conversion by retaining oxygen.
- The addition of ethanol to fuel drastically reduced particulate and hydrocarbon emissions. The decrease in these emissions can be explained by ethanol being rich in oxygen content. When propolis was added to ethanol, a further decline was noted.
- The temperature of the exhaust gas and NO_x emissions decreased due to the addition of ethanol to diesel fuel. In-cylinder pressure and heat release rate decreased because of ethanol's low calorific value. With the addition of propolis dissolved in ethanol, a further drop was observed in exhaust gas temperature and NO_x emission due to the lower heating value of the additives.

- When ethanol was added to diesel fuel, thermal efficiency and brake-specific fuel consumption both changed: the thermal efficiency decreased, and the brake-specific fuel consumption increased. The fuel consumption increased because of ethanol's lower calorific value. The heating value of propolis drops when it is dissolved in ethanol, which can be considered to be the cause of the decline when ethanol is added to the propolis additive. It was shown that adding ethanol with propolis adjuvant had the opposite impact of the decline in thermal efficiency on brake-specific fuel consumption.
- O₂ emission increased with the addition of ethanol to the fuel. A minimal increase was obtained when propolis was added.
- Future studies can focus on fine-tuning the concentration of propolis in the fuel blend to maximize emission benefits while minimizing negative impacts on engine performance and fuel efficiency.
- Investigating the long-term effects of these fuel blends on engine wear and durability can prove crucial for practical applications.
- Testing these fuel blends in a variety of engine types and configurations can provide a more comprehensive understanding of their applicability and effectiveness.
- A holistic environmental impact assessment, including a lifecycle analysis of CO₂ emissions, will be beneficial in providing a full understanding of the environmental implications of using such fuel blends.
- Assessing the economic aspects of producing and using ethanol and propolis-enhanced diesel fuels is essential for their potential market adoption.
- Exploring other natural additives similar to propolis can also yield interesting and potentially more effective results in improving diesel fuel performance and emission characteristics.

By addressing these areas, future studies can build upon the findings of this study to develop more sustainable and efficient fuel options for diesel engines.

CRedit authorship contribution statement

Serhat Kocyiğit: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation. **Salih Özer:** . **Samet Çelebi:** . **Usame Demir:** Writing – review & editing, Writing – original draft, Methodology, Investigation.

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

No data was used for the research described in the article.

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