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An Experimental Study On The Performance And Exhaust Emission Characteristics Of A CI Engine Powered By Alcohol/Biodiesel/Diesel Fuel Blends Containing Different Types Of Alcohol (Isopropanol-C3, 1-Butanol-C4, And Isopentanol-C5)

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ABSTRACT

Alcohols are significant alternative and renewable fuel candidates for the utilization in the internal combustion engines due to encouraging favorable environmental and economic outputs. Long-chain alcohols have various advantages over short-chain alcohols because of their larger energy content, elevated cetane number (CN) and preferable blending properties, etc. The objective of the present experimental research deal with the exploring and compare the influence of the ternary fuel mixtures of petroleum-based diesel fuel, cottonseed oil methyl ester (COME) and long-chain alcohols of isopropanol (Pr), 1-butanol (Bt), and isopentanol (Pt) on the performance and emission characteristics of a single-cylinder, four-stroke, naturally-aspirated, direct-injection compression-ignition (CI) engine. As the prepared tested fuel samples, four different blends were as follows on a volume basis: B20 (20% COME + %80 diesel fuel), B20Pr20 (20% COME + %20 isopropanol + %80 diesel fuel), B20Bt20 (20% COME + %20 1-butanol + %80 diesel fuel), and B20Pt20 (20% COME + %20 isopentanol + %80 diesel fuel). The engine trials were carried out at various loads (0-1250 W) and under a constant speed (3000 rpm) to observe the aforementioned behaviors. Based on the experimental outcomes, brake specific fuel consumption (BSFC) values of B20Pr20 exhibited higher than those of other ternary blends at all loads. Brake thermal efficiency (BTE) values for B20Pt20 were observed as larger than those of ternary blends. B20Pt20 had higher exhaust gas temperature (EGT) values than those of B20Bt20 and B20Pr20. The infusion of long-chain alcohols to COME/diesel blend caused to reduce NO_X emissions meanwhile isopropanol, 1-butanol, and isopentanol were the most to least influential alcohol types, respectively. Besides, with the addition of alcohol, a substantial decrement was noticed in smoke opacity at entire loads owing to the excess amount of oxygen content and lesser ratio of C/H of the alcohols. However, CO and HC emissions rose by infusion of long-chain alcohols to the blends. Finally, it can be concluded that higher alcohols could be a possible fuel additive for the fractional replacement for petroleum-based diesel fuel and biodiesel in the blends for CI engine practices.

Keywords:
Cottonseed oil methyl ester, Long-chain alcohols, Performance, Emission, Diesel engine

INTRODUCTION

Diesel engines or CI engines have been taken into consideration to be a vital and important power source all over the world for various areas such as transportation (land, air, and sea), agriculture, power generation, industrial activities, and construction engineering sectors because they have high-performance features [1-3]. Diesel engines possess also capacity in terms of supplying higher torque, higher power outcome, higher durability and superior fuel conversion efficiency in comparison with the spark ignition engines [4]. The aforementioned characteristics, therefore, showed that diesel engines are preferable selection as compared to the gasoline engines considering the widespread area of applications [5]. Unfortunately, diesel engines are largely depended on the fossil-based fuels. The pollutants released from the engines have been increased worldwide owing to the production as well as consumption of

Nomenclature

BSFC	Brake specific fuel consumption (g/kWh)
BTE	Brake thermal efficiency (%)
CA	Crank angle (degree)
COME	Cottonseed oil methyl ester
CN	Cetane number
CI	Compression-ignition
Pr	Isopropanol
Bt	1-butanol
Pt	Isopentanol
B20	20% COME + %80 diesel fuel
B20Pr20	20% COME + %20 isopropanol + %80 diesel fuel
B20Bt20	20% COME + %20 1-butanol + %80 diesel fuel
B20Pt20	20% COME + %20 isopentanol + %80 diesel fuel
D100	Diesel fuel
EGT	Exhaust gas temperature (°C)
TDC	Top dead center
EGR	Exhaust gas recirculation
NaOH	Sodium hydroxide
CO	Carbon monoxide (%)
LHV	Latent heat of vaporization (kJ/kg)
HC	Unburned hydrocarbon (ppm)
ID	Ignition delay (degree)
NOx	Oxides of nitrogen (ppm)
NO_2	Nitrogen dioxide (ppm)
NO	Nitrogen monoxide (ppm)
CO2	Carbon dioxide (%)
R	Dependent factor
X	Independent variables
W	Uncertainty value

fossil-based fuels. By all means, most of the pollutants have been spread because of the utilization of diesel fuel [6, 7]. The portion of contaminants in the overall atmospheric air pollution brought about by transportation vehicles powered by diesel engines has been augmenting along with the rise of these vehicles in the world [8]. From those issues, it is to be noted that alternative, renewable, sustainable and clean fuel resources for diesel engines have to be searching because of the motivating parameters related to the fluctuations in the petroleum prices, concerns with global warming, toxic pollutants released from the engines and strict emission legislation [9-13].

Alternative fuel resources have commenced acquiring higher popularity by countries owing to their capability in the reduction of greenhouse gasses, presence in nature and availability, less dependency on petroleum imports, etc. [14, 15]. Among the above-mentioned sources, biodiesel and alcohols have great potentials in the countries where have a higher amount of biomass capacity. Also, they are come up with alternative candidates for replacement over diesel fuel [16]. Biodiesel can be briefly described as the mixture of the mono-alkyl esters of long-chain fatty acids synthesized from different raw materials like vegetable oils, animal fats and their wastes, etc. [17]. Although there are different techniques (dilution, pyrolysis, transesterification, microemulsion) to obtain biodiesel, the transesterification method has been mostly used by researchers [18, 19]. One of the most significant characteristics of biodiesels is to being possess lesser emissions in comparison with mineral diesel fuel. Biodiesel is an alternative, renewable, non-toxic, environmentally-friendly, sulfur-free, and clean fuel [20, 21]. Biodiesel fuels have not only direct use in diesel engines but they can be also used by mixed with conventional diesel fuel at any concentrations [22]. However, the diesel engines have not been operated with pure biodiesel up to 100% out of any engine alteration because of its higher density and viscosity values. In addition, the worse low-temperature properties for biodiesel fuels are limited in terms of direct usage. The above mentioned worse characteristics of biodiesel can be eliminated with blending alcohols [23, 24]. Alcohol can be synthesized from renewable raw materials like biomass, thus, it is an important renewable fuel [25]. On the other hand, alcohols have a few substantial disadvantages like low CN, high latent heat of vaporization (LHV). It can be clearly, therefore, stated that the alcohols could not be preferred as a fuel in CI engines directly [26].

As known, the fuel properties of biofuels have to be enhanced and brought closer to the traditional diesel fuel before using in the diesel engines. Many fuel specifications like viscosity and density can be developed with the supplementation of various types of alcohols to biodiesel or diesel fuel/biodiesel mixtures [27, 28]. When the present literature was surveyed, such researches performed and the focus on the point of these investigations has generally been related to the diesel fuel/biodiesel mixtures and the infusion of particular alcohols into those blends [29-31]. The researchers have been the most commonly tested biodiesel produced from various vegetable oils and ethanol (C_2H_5OH) as renewable, sustainable, and alternative fuels in CI engines at several proportions [32, 33]. Ethanol leads to separation of phase above 10°C when it is mixed with biodiesel or diesel fuels to power the CI engines [34]. Besides that, ethanol cannot be blended with pure diesel fuel with high proportions due to less CN resulting in ignition delay (ID), low energy content and worse lubricity characteristic of ethanol [35]. Noteworthy, it has been considered that alcohol can be more smoothly blended with biodiesel and diesel fuels regarding the increase of carbon atoms in the chemical bonds of the alcohol. Moreover, the rise of the carbon atom number inside the alcohol causes to boost CN, energy capacity, viscosity, and density while decreasing the excessive amount of inherent oxygen content. Concerning the quantity of carbon atoms in the chemical bonds of long-chain alcohols such as propanol-C_3H_7OH, butanol-C_4H_9OH, and pentanol-C5H11OH have higher energy contents, densities, viscosities, CN, flame speeds even though they have lower LHV, risk of corrosion, and ignition temperature [36, 37]. When the literature was comprehensively evaluated, there is a limited number examination with respect to the investigation of propanol with blending biodiesel and diesel fuels on the influences of the engine characteristics involving performance, emissions, and combustion [38-41]. No doubt that the recent literature has exhibited numerous papers investigating the butanol blends with diesel and biodiesel [4, 25, 42-49]. However, the researches that use of many pentanol isomers as alternative additives for diesel fuel and biodiesel have not been enough. For instance, Campos-Fernández et al. [50], Li et al. [51, 52], Yang et al. [53], Santhosh et al. [54] and Sridhar et al. [55] studied the effects of pentanol on the engine performance, emissions, and combustion behaviors of different types of diesel engines.

Based on the aforementioned studies conducted by various researchers, butanol and pentanol might be tested to be as oxygenated fuel additives for diesel fuel, biodiesel, and their blends out of any major alteration on the engine. In addition to this, these researches have approved that the higher-order alcohols such as butanol and pentanol have been found to be more powerful additives than short-chain alcohols in terms of improving the fuel properties of biodiesel, and hence, they can be accepted as next-generation biofuels owing to the above-mentioned potentials. In spite of the fact that there are many researches regarding the higher-order alcohols as referring above, as far as the author knows that there is a skimpy number of papers in the recent literature for the assessment of propanol, butanol, and pentanol in the identical test engine. Some of them were summarized as follows: Atmanli [8], for instance, performed comparative analyses of waste oil biodiesel/diesel fuel and propanol, n-butanol or 1-pentanol blends in a CI engine to observe the performance and emissions levels. The researcher found that the supplementation of the above-mentioned higher-order tested alcohols to the biodiesel/diesel fuel blend inspired to enhance the cold flow specifications. BSFC for ternary blends increased owing to the lower calorific values of the alcohols in the meantime BTE augmented. All the tested long-chain alcohol fuel samples boosted CO emissions meanwhile NO_X emissions decreased in contrast to the diesel/biodiesel fuel blend. Jin et al. [9] scrutinized the impacts of the different kinds of propanol (n-propanol, iso-propanol), butanol (n-butanol, iso-butanol, sec-butanol, tert-butanol), and pentanol (n-pentanol, iso-pentanol, tert-pentanol) on the solubility of alcohol/diesel mixtures. Kumar and Saravanan [36] reviewed the usage of higher-order alcohols in the CI engines comprehensively. Kumar et al. [41] optimized the performance and emission features of a DI diesel engine fueled with the blends of diesel/n-propanol, n-butanol or n-pentanol applying statistical approach such as response surface methodology. The best engine configurations were monitored for diesel/n-propanol as injected at 25o crank angle (CA) before top dead center (TDC) with 30% exhaust gas recirculation (EGR) and for others, as injected at 24^o CA before TDC with 10% EGR. Ghadikolaei et al. [56] scrutinized the performance, combustion, and emission patterns of a CI engine running on diesel/biodiesel/alcohol (methanol-C1, ethanol-C2, propanol-C3, butanol-C4, and pentanol-C5) blends. Interestingly, the researchers ensured the blends with the same oxygen concentration as 5%. They concluded that the methanol blend exhibited the best performance with least emission profiles amongst the tested fuel blends. Yilmaz et al. [57] experimented the influence of the several higher-order alcohols such as propanol, n-butanol, and 1-pentanol addition into the methyl ester obtained from waste oil on the performance and emission properties of a CI engine under diverse engine loads (0, 3, 6, and 9 kW) and a constant speed of 1800 rpm. As a result, they highlighted that 10% (by volume) alcohol addition into the waste oil methyl ester seems reasonable to accept as an alternating to traditional fossil-based diesel fuel taking into account their higher BSFC figures. Atmanli and Yilmaz [58] examined the combustion features of a CI engine under the semi-low temperature fuelled condition with waste oil biodiesel/alcohol (propanol-C3, n-butanol-C4, and 1-pentanol-C5). They marked that all of the tested alcohols in the experiments have been found to be candidates for diesel engines in the reduction of harmful gases released from the engine. As observed, currently published papers in this subject figured out many outcomes on the influences of higher alcohols concerning the performance and exhaust gas pollutants in the CI engine. The present experimental examination was performed so as to complete the above-mentioned gap since the comparison of performance and emission characteristics of the handled alcohols have not been scrutinized in detail.

In the present work, as alternative and clean fuels, the long-chain alcohols of isopropanol, 1-butanol, and isopentanol were blended with diesel fuel and COME as a fractional substitution in CI engine applications. The methyl ester namely alternative biodiesel fuel from the cottonseed oil was produced via implementing a single-step transesterification reaction using methanol in the presence of NaOH. For preparing the tested fuel samples, 20% (by volume) isopropanol, 1-butanol, and isopentanol was added into the diesel/COME blend to obtain B20Pr20, B20Bt20, and B20Pt20. In order to evaluate the performance and emission characteristics of a single-cylinder, four-stroke, DI diesel engine, the trials were conducted on under five dissimilar engine loads (0-1250 W) with a fixed speed (3000 rpm) for each tested fuels. Afterward, the results coming from the experiments were meticulously compared with the reference fuels those are diesel and diesel/COME blend.

Table 1. The key fuel characteristics of the tested fuel samples

No	Property	Unit	D100	B20	B20Pr20	B20Bt20	B20Pt20	Isopropanol	1-butanol	Isopentanol
1	Density at 15°C	kg/m³	825	838	830	834	835	784	807	812
2	Kinematic viscosity at 40°C	mm²/s	2.539	3.011	2.857	2.955	3.088	1.769	2.258	2.923
3	Lower calorific value	kJ/kg	43571	42306	39322	40192	40540	28652	33002	34741
4	Cetane number	-	52.30	51.04	42.98	43.98	44.58	12[1]	17[1]	20[1]
5	Carbon	wt. %	87.05	84.64	79.23	80.20	80.87	60.00	64.87	68.18
6	Hydrogen	wt. %	12.95	12.96	13.04	13.07	13.10	13.33	13.51	13.64
7	Oxygen	wt. %	0	2.40	7.73	6.73	6.03	26.67	21.62	18.18
8	Carbon/Hydrogen		6.722	6.531	6.078	6.136	6.174	4.501	4.802	4.999
9	Water content	ppm	23	118	230	185	279	580	350	820
10	Latent heat of evaporation[1]	kJ/kg	270-375	-	-	-	-	727.88	581.4	308.5
11	Copper strip corrosion[2]	Degree of corrosion	la	la	la	la	la	-	-	-

[1] These values were adopted from Kumar and Saravanan [36]
[2] 3 h at 50°C

MATERIALS AND METHODS

In this experimental research, the influences of different kinds of alcohol infusion into the biodiesel/diesel mixture on the engine performance and emissions patterns have been explored elaborately. For the aforementioned intent, diesel fuel, cottonseed oil methyl ester (COME), and alcohols (isopropanol-C3, 1-butanol-C4, and isopentanol-C5) have been used during the experiments. Isopropanol (99.7% purity) and 1-butanol (99% purity) were bought from Emir Chemical (Ankara-Turkey) while isopentanol (>98% purity) was supplied from Tekkim Laboratory Chemicals (Bursa-Turkey). During the engine test, commercially available diesel fuel purchased from a regional oil station (Yozgat- Turkey) was experimented in order to get the baseline data. Diesel fuel was called as D100.

The biodiesel fuel was produced by implementing a laboratory-scale single-step transesterification process in the Biofuel Laboratory, Mechanical Engineering Department, Yozgat Bozok University (Yozgat-Turkey). The transesterification technique using methanol (99.8% purity) and sodium hydroxide (NaOH) pellets (99% purity) was used to prepare the COME. Cottonseed oil was taken from a local market (Ankara, Turkey). In order to produce the COME, the optimum transesterification reaction conditions were applied as follows: reaction temperature of 60°C, methanol to oil molar ratio of 6:1, reaction duration of 60 min, and catalyst concentration of 0.6%. More detail about the production of biodiesel from cottonseed oil can be also come across in the previous work of the author [59].

COME was mixed with pure diesel at the proportion of 20% on a volume basis and coded as B20 (20% COME + %80 diesel fuel). Later, the above-mentioned higher-order alcohols were mixed with B20 at the same ratio with biodiesel, i.e., 20% (by volume) decreasing the diesel concentration in the blend. These blends are called as B20Pr20 (20% COME + %20 isopropanol + %80 diesel fuel), B20Bt20 (20% COME + %20 1-butanol + %80 diesel fuel), and B20Pt20 (20% COME + %20 isopentanol + %80 diesel fuel). Some of the physicochemical specifications of the chosen alcohols in the current study and the key fuel characteristics of the tested fuel specimens used in the engine trials were presented in Table 1.

The diesel engine experiments were executed at several loads such as 0 W, 500 W, 750 W, 1000 W, and 1250 W under the fixed speed (3000 rpm). To eliminate the errors, all of the fuel specimens were tried under almost identical working conditions. All of the parameters coming from the engine tests were compared with the reference D100 and B20.

The diagrammatic appearance of the experimental layout was technically illustrated in Fig. 1. The engine trials have been achieved in a single-cylinder, DI diesel engine. This diesel engine was mounted on a generator and the series of electrical resistance components were placed to load this test engine. The technical properties of the diesel power generator were given in Table 2. The engine experiments were performed without any engine modification. Besides, all data were recorded during the tests whenever the tested engine attained the conditions of steady-state. For this purpose, the engine had been operated at least 15 minutes, before each experiment commenced.

The emission patterns (carbon monoxide, carbon dioxide, unburned hydrocarbon, and nitrogen oxides) and smoke opacity data of the fuels used in this study were measured with the assistance of a gas analyzer and opacimeter (Italo Plus-Spin type). Table 3 showed the range of the measurement and accuracy values of the exhaust gas analyzer and opacimeter. Prior to the emission measurement, the gas

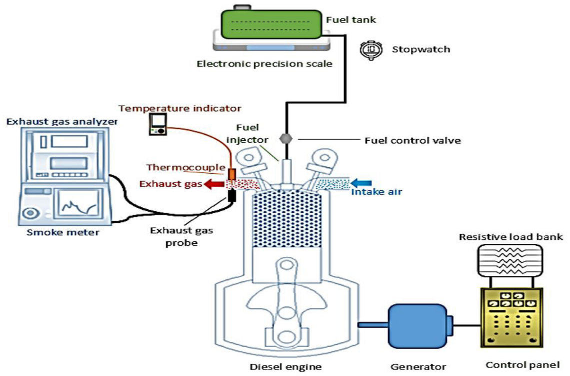

Figure 1. The schematic diagram of the experimental setup

Table 2. Technical specifications of the diesel power generator

Diesel engine		Generator	
Manufacturer	Katana	Manufacturer	Katana
Model	Km 178Fe	Model	KD 4500E
Cylinder number	Single-cylinder	Maximum power	4.2 kVA
Cycle number	Four	Power	3.6 kVA
Bore x Stroke	78 mm x 62 mm	Phase	1
Volume of cylinder	296 cm^3	Voltage	230 V
Power output (Continuous)	6 hp	Frequency	50 Hz
Power output (Maximum)	6.7 hp		
Speed	3000 rpm		
Compression ratio	18:1		
Injection system	DI		
Cooling system	Air-cooled		
Injection timing	31^obTDC		
Injection pressure	200 bar		
Intake system	Naturally-aspirated		
Injector nozzle number	4		

sensors of the device were calibrated thanks to the standard gases so as to keep away from the faults. To get each exhaust gas emission findings and to avoid unsteadiness, the measurements were carried out at least five times at a similar interruption and their averages were calculated and presented in this study.

To measure the EGT values for the tested fuels, a K-type thermocouple was embedded on the exhaust pipe. As observed from Fig. 1, the consumption of the tested fuel samples was assigned in mass using a stopwatch and an electronic precision scale. As a measure, the fuel consumption of all the fuel samples, the initial and final mass was recorded each 15 minutes duration at each engine load operating condition.

As is well known that, the probability of errors occurring

Table 3. Technical properties of the exhaust gas analyzer and opacimeter

Parameter	Unit	Range	Accuracy
CO	%	0-9.99	± 0.06
CO2	%	0-19.99	± 0.05
HC	ppm	0-2500	± 12
NOx	ppm	0-2000	± 5
Smoke opacity	%	0-99	± 2
EGT	^0C	0-750	± 1
Operating temparature	^0C	5-40	
Storage temperature	^0C	(-20)-(+60)	
Feed voltage	V DC	12	

in any examination is high in the course of whole investigations. Indeed, many errors form from the side of the researcher though some of them are randomly comprised. In plenty of cases, the uncertainty of the investigation is commonly overcome by exerting the increase of the experimental run. On the other hand, sometimes there may be no chance of repeating experiments owing to the particular conditions that high-cost studies may be executed. Accordingly, the researchers should be meticulous and attentive in order to ensure the experimental findings for reducing the errors. With this intend, the uncertainties of the used apparatuses in the present research like exhaust gas emission sensors, temperature sensor, etc. were considered [60]. It is to be noted that the uncertainty values of the findings of the current work can be estimated in accordance with the square root method by using Equation (1) [61-63]. The values of the uncertainties as percentages for the detected parameters have been shown in Table 4.

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2} \quad (1)$$

where;

- R: Dependent factor,
- x: Independent variables,
- w: Uncertainty value.

As a result, the entire uncertainty value coming from the types of equipment used in the experiments was calculated as ±2.74% applying the formula given underneath. It can be concluded that this value is well within the acceptable limits [64, 65].

$$\begin{aligned} &\textit{Overall uncertainty} = \textit{Square root of } \{(\textit{uncertainity of BSFC})^2 \\ &+(\textit{uncertainity of BTE})^2 + (\textit{uncertainity of CO})^2 + (\textit{uncertainity of NOx})^2 \\ &+(\textit{uncertainity of HC})^2 + (\textit{uncertainity of } CO_2)^2 + (\textit{uncertainity of smoke})^2 \\ &+(\textit{uncertainity of EGT})^2\} \end{aligned} \quad (2)$$

Table 4. Uncertainties values of the measured parameters

No	Instrument	Uncertainty (%)
1	Load indicator	± 0.5
2	Temperature sensor	± 1.0
3	Speed	± 0.2
4	Smoke meter	± 1.0
5	Precision scales	± 0.5
6	Digital stop watch	± 0.2
7	Exhaust gas analyzer	
	CO	± 0.4
	CO_2	± 0.6
	HC	± 0.5
	NOx	± 0.9

$$= Square\,root\,of \begin{Bmatrix} (1.4)^2+(1.4)^2+(0.4)^2+(0.9)^2 \\ +(0.5)^2+(0.6)^2+(1.0)^2+(1.0)^2 \end{Bmatrix} \quad (3)$$

$$= 2.74\% \quad (4)$$

RESULTS AND DISCUSSION

The performance and emission patterns for all the tested fuels (D100, B20, B20Pr20, B20Bt20, and B20Pt20) have been detected under different engine loads from 0 W to 1250 W and at a fixed speed (3000 rpm). In the course of the research, great deals of parameters have been evaluated and the aforementioned experimental outcomes have been taken into account so as to compare with the conventional baseline D100 and B20 fuel blend. In addition, these findings were comprehensively discussed considering the recent literature in this section which was presented underneath.

3.1. Engine performance characteristics

The BTE, BSFC, and EGT have been regarded the principal factors which have been benefited to identify the engine performance properties of a test engine while it is being run on the suited fuel samples. These major parameters are discussed in the below subsections point by point.

3.1.1. Brake thermal efficiency

BTE is summarized as being the efficiency of chemical energy conversion to the effective work obtained from the internal combustion engine. BTE is depended upon the net calorific value of the used fuel in the test engine since it is the rate of the output power to the heat ensured from the fuel [66]. Change of BTE values for the D100, B20, B20Pr20, B20Bt20, and B20Pt20 against the engine load was shown in Fig. 2. As it is obvious from the graph, BTE rises along with a promotion in load and the maximum results have been appeared under the highest condition operating condition. This case can be explained with much more fuel is spent at the higher loads able to generate a higher output of power in the engine [67]. The peak BTE values were observed by D100 all of the loads that are owing to its highest content of the energy of 43.571 MJ/kg. In contrast to D100, the lowest BTE values were obtained by B20Pr20 at all loads. It can be predicated to the fact that the net calorific value namely energy content of isopropanol (28.652 MJ/kg) is the least among the tested fuel samples, as seen in Table 1. Besides, B20 blend fuel shows lower values than that of pure D100 because of worse viscosity and atomization characteristics of the biodiesel fuel [68]. Actually, the B20Pt20 fuel blend is displayed by comparatively higher BTE values than those of ternary blends as a result of the existence of D100 that satisfies a reduction in the energy content of COME. At the maximum load, BTE values of D100, B20, B20Pr20, B20Bt20, and B20Pt20 were found to be at 23.83%, 21.51%, 18.24%, 19.75%, and 20.36%, respectively. As expected, all the ternary blends figure lesser BTE values than that of B20 at entire loads. This is because of the tested alcohols in the blends which they have less net calorific value than diesel fuel resulting in the reduction of calorific value of the blend [69]. Isopentanol has the highest net calorific value than those of other alcohols used in the present study. Moreover, similar trends have been indicated by Ning et al. [29] and Silintonga et al. [70]

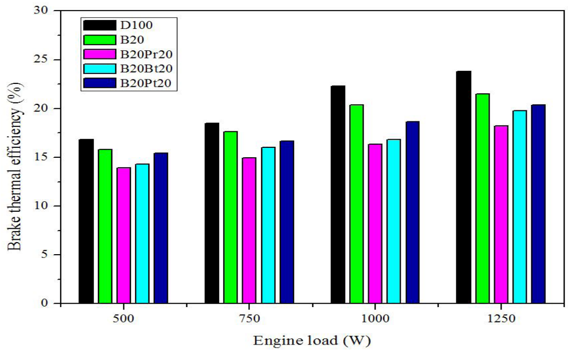

Figure 2. Change of BTE against the engine load

3.1.2. Brake specific fuel consumption

BSFC infers a comparison amongst the fuel quantity extinguished in any engine and the corresponding power generated by the engine. Indeed, it is an important indicator for the efficiency of the fuel consumed of an engine, and therefore, it permits the comparison of fuel efficiency for various engines directly [4]. Fig. 3 portrays the change of BSFC values as a function of load for the tested fuel samples. It is to be noted that BSFC declines with the promotion of the load because it is a good agreement with the fact that larger fuel injection pressure and extended duration provided for fuel to mix in the chamber of combustion under the elevated loads exists. Based on the before mention, the minimum BSFC values for the tested fuel specimens were encountered to be as the highest load in this work [71, 72]. At 1250 W, BSFC values were calculated as 351.64 g/kWh for D100 and 397.52 g/kWh for B20. As seen, the B20 fuel blend shows a slightly larger BSFC than that of traditional D100. This case is a common inclination for the plenty of the alternative and renewable fuel candidates since they have lesser energy content than that of diesel fuel. It is an important factor to acquire a similar output power from the engine [69]. This can be also explained by the inappropriate atomization behaviors and high spray penetration of biodiesel fuel [73]. It is to be noted that this is led owing to a substantial descending in the net calorific value of the biodiesel fuel and not only its higher viscosity but density values also exhibit a basic role in the consumption of the fuel throughout the engine operation [74]. Moreover, the BSFC results for the ternary blends of 20% (by volume) ratio of isopropanol, 1-butanol, and isopentanol at the highest load are determined to be as 508.51 g/kWh, 458.28 g/kWh, and 437.59 g/kWh, respectively. The BSFC values for B20Pr20, B20Bt20, and B20Pt20 fuel blends were averagely by 41.97%, 32.40%, and 22.15%, respectively higher than that of D100 while averagely by 28.29%, 19.65%, and 10.40%, respectively higher than that of the B20 blend. Noteworthy, it was evident that BSFC values for isopentanol infused ternary blend are lower than those of other ternary blends. This is because of the larger energy amount of the isopentanol than that of tested higher-order alcohols, as shown in first Table. These findings have been a good agreement with the findings put forth by Babu and Anand [75] as well as Devarajan et al. [76].

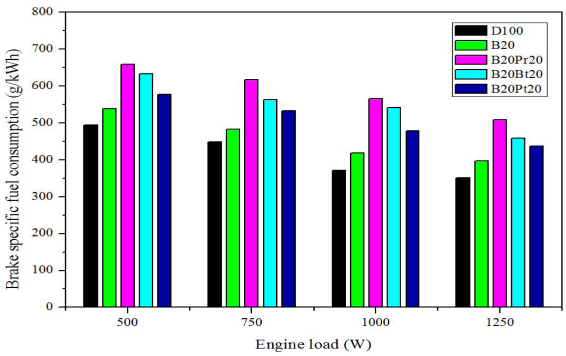

Figure 3. Change of BSFC against the engine load

3.1.3. Exhaust gas temperature

The change of the EGT with respect to the load for various fuels has been demonstrated in Fig. 4. It is anticipated from this research that the maximum EGT values are determined at the peak load operating condition. EGT values are ascended with the increase of the load for whole the fuel specimens [77, 78]. The minimum EGT values for D100, B20, B20Pr20, B20Bt20, and B20Pt20 were observed to be as in the order of 137°C, 121°C, 99°C, 108°C, and 115°C while the maximum EGT values were found to be at 298°C, 263°C, 234°C, 244°C, and 256°C, respectively. As seen, the peak EGT values at all engine loads have occurred with pure diesel fuel. The EGT is a significant indicator that influences the exhaust gas pollutants released from the engine. Normally, EGT can change depending upon the operating conditions of the engine like injection pressure, compression ratio, engine speed, engine load, etc. and specifications of the consumed fuel like net calorific value, viscosity, CN, density, etc. [79]. It is evident from the graph that there is a considerable variation between the experimental findings for the used fuel samples. The supplementation of biodiesel into D100 inspired reductions in EGT values due to lesser energy content of biodiesel [80]. A similar trend was also seen in the ternary blends. The alcohol infusion to the B20 blend has led to a decrease in the values of EGT [81]. The minimum EGT values at all engine loads were observed using isopropanol blended fuel sample because of the net heat capacity of the isopropanol, as presented in Table 1. Among the ternary blends, the maximum values were achieved with isopentanol owing to the above-mentioned reason. The alcohols can draw back the heat energy from the surrounding region because they have high LHV. Hence, EGT values decrease significantly when the test engine powered by the alcohol added fuels [82]. LHV of the tested alcohols can be seen in Table 1 and it can be ordered from highest to the lowest as follows: isopropanol, 1-butanol, and isopentanol. Accordingly, the EGT values can be sorted from highest to the lowest as follows: isopentanol, 1-butanol, and isopropanol. In this way, the EGT alteration was validated. One has not passed without saying the situation that this can be linked to the lower end temperature of the combustion occurred inside the cylinder when diesel engine fuelled with the tested fuel samples that have a high native content of oxygen in the chemical bonds as well as lower heat capacity [56]. It is stated to be in other words that the higher concentration of oxygen amount in the chamber of combustion leads to a decrease in EGT values by improving the combustion efficiency as compared to conventional diesel fuel [81, 83].

3.2. Exhaust emission parameters

This section indicates a comprehensive and detailed discussion on the exhaust gas patterns like carbon monoxide (CO), unburned hydrocarbon (HC), carbon dioxide (CO_2), oxides of nitrogen (NO_X), and smoke opacity measured from the experiments conducting diesel fuel, diesel/biodiesel blend, and ternary blends of alcohol/biodiesel/diesel at desired loads.

3.2.1. Hydrocarbon emissions

The unburned HC of any engine is key evidence of the attribute of the combustion reaction. The factors such

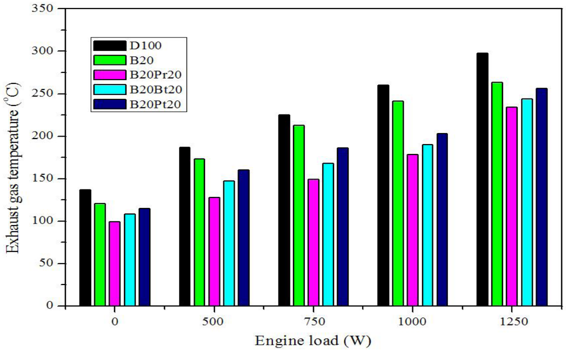

Figure 4. Change of EGT against the engine load

as spray characteristics of the fuel, air/fuel ratio, fuel properties, and engine working circumstances affect unburned HC emission formation inside the cylinder [4, 84]. Fig. 5 depicts the change of HC emissions of the tested fuel samples concerning the loads. As figured out from the illustration, the conventional diesel fuel releases the highest concentration of HC emissions than that of performed fuel samples at entire loads. COME that is an alternative fuel as biodiesel has a native content of oxygen in the chemical structure contrary to mineral diesel fuel. D100 is composed of pure hydrocarbon chains. Similar outcomes have been also reported by many kinds of literature operating with various biodiesel fuelled CI engine [67, 85, 86]. At 1250 W operating conditions, the maximum HC emission for D100, B20, B20Pr20, B20Bt20, and B20Pt20 were found to be at 365.82 ppm, 329.42 ppm, 262.99 ppm, 283.92 ppm, and 296.66 ppm, respectively. On average, B20 fuel blend exhibited a 9.20% reduction in HC emission in comparison with that of D100 while B20Pr20, B20Bt20, and B20Pt20 showed decreases by 30.40%, 22.19%, and 16.20%, respectively. As is well known that the alcohols possess abundant oxygen molecules in their structure and thence they are oxygenated fuel additives for the diesel. Accordingly, isopropanol, 1-butanol, and isopentanol have approximately 26.67%, 21.62%, and 18.18% oxygen content, respectively. By virtue of the entity of a surplus quantity of oxygen molecules inside the chamber of combustion, ternary blends of COME, alcohol, and D100 are contemplated to emit a lower concentration of HC emission during the combustion. In fact, the outcomes coming from the experimentations have been shown that the HC emissions increase by adding higher-order alcohols into the blends. The minimum results were observed with the usage of B20Pr20 whereas the B20Pt20 blend fuel released maximum HC emission to the environment among the ternary blends. It can be attributed to the combined impact of the LHV and the quality of the ignition of the tested alcohols [84]. The higher LHV (as seen in Table 1) causes to retract the heat from the combustion chamber, i.e., quenching effect inside the cylinder [87]. Moreover, a lower CN elongates the ID period. These effects have control over the other influences of blended fuel samples such as improved atomization property which encourages better combustion process inside the chamber of combustion. As the long duration for combusting that decreased auto-ignition properties present for long-chain alcohols blended fuel samples which cause to forms leaner external flame regions in the cylinder resulting in larger HC emissions [42].

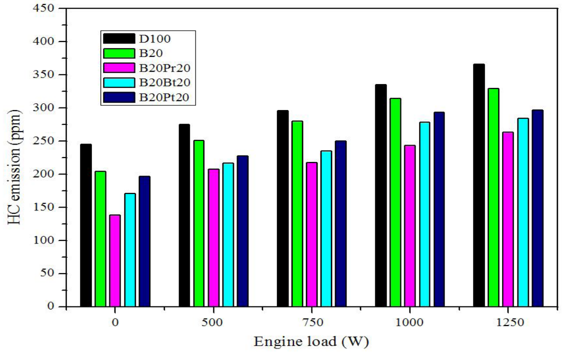

Figure 5. Change of unburned HC emissions against the engine load

3.2.2. Carbon dioxide emission

Fig. 6 illustrates the CO_2 emissions in percentages in accordance with the loads for the tested fuels. It has been clearly determined by monitoring the figure that the engine loads were increased, the CO_2 emission levels violently increased [88]. The aforementioned increase in CO_2 emission patterns can be linked to the rise in BSFC in consequence of BTE with an ascending in engine load. Not interestingly, diesel portrays the lowest CO_2 emissions at entire the engine loads since petroleum-based diesel fuel has high energy content, elevated BTE as well as better atomization characteristics causes to reduce the CO_2 emissions. The long-chain alcohols because of their native oxygen content in the molecular structure react lightly with CO molecules and hence the formation of CO_2 emissions increases [89]. Therefore, it is difficult to say that higher alcohols have little or no effect on CO_2 emissions. The CO_2 emissions for D100, B20, B20Pr20, B20Bt20, and B20Pt20 at 1250 W engine load were noticed to be as 7.15%, 7.42%, 8.64%, 9.00%, and 10.33%, respectively. The lesser viscosity and density values resulting from the alcohol addition to the B20 blend have improved the vaporization process of fuel inside the cylinder and therefore the CO_2 emission was increased [75]. Similar findings have been also obtained in Refs. [90, 91].

3.2.3. Oxides of nitrogen emission

The emissions of NO_X in the exhaust gases of diesel engine composes of heavily nitrogen monoxide (NO) and nitrogen dioxide (NO_2) [92]. The NO_X emissions are affected from several factors such as the oxidation of nitrogen is found in the atmosphere under an elevated temperature of the combustion chamber, the oxidation reaction of nitrogen coming from the fuel chemical structure,

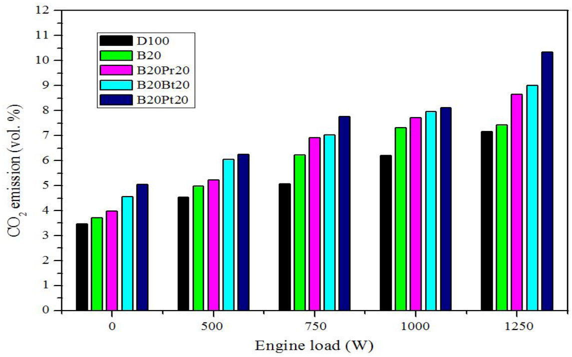

Figure 6. Change of CO_2 emissions against the engine load

through decline on CN group forming intermediate species such as ketones, NO_X, etc. ın other words, the abovementioned parameters are largely accountable from the increasing the formation of NO_X in CI engines [73]. The alteration of NO_X emissions for the tested fuel samples used in this experimentations with regard to the loading is presented in Fig. 7. Not only as is well known from the literature, but also theoretically, biodiesel fuels have been emitted higher amount of NO_X emissions when compared to the neat D100 on account of the being of inherent oxygen molecules in their molecular bonds [93]. This case can be also validated from the graph given underneath. It was distinct from Fig. 7 that the NO_X emission of the B20 blend was the highest amongst the other all the tested fuels due to the aforementioned reason. At 1250 W operating condition, the NO_X emission of B20 was observed to be as 56.94% which was more than that of D100. It is to be noticed from the measurement that the NO_X emissions raised with the increment in the load and the highest results were obtained at the peak load (1250 W). Namely, the current research showed the NO_X emissions for entire the tested fuel specimens were predicted concerning the brake power. Hence, the increasing inclinations were monitored with the increase in the load. By the way, the lowest NO_X emissions were normally observed with reference fuel (D100). The NO_X emissions for D100, B20, B20Pr20, B20Bt20, and B20Pt20 were averagely measured as 197.11 ppm, 293.20 ppm, 206.39 ppm, 230.96 ppm, and 248.98 ppm, respectively. As observed, the addition of various alcohols to the diesel/biodiesel blend caused to decrease the NO_X pollutants slightly because of the 20% fraction in the blend. It was evident from the figure that the high LHV of alcohol (as given in Table 1) leads to becoming a cooling impact inside the engine cylinder even though an excessive amount of oxygen content is found in the alcohol. Hence, the aforementioned characteristics cause the reduction of the combustion chamber temperature resulting in assist to decline the formation of NO_X emission since the NO_X generation is led by both the abundance of the oxygen molecule in the cylinder and the combustion temperature [94, 95]. On the other hand, from the graph, it can be appeared that the decrement in the NO_X emission is comparatively lower for the B20Pt20 blend as the isopentanol has a higher CN than those of isopropanol and 1-butanol which enhances the combustion process in the cylinder. CN may be correlated with the ID duration of the engine [96]. A higher CN leads to a decrease in the ID period. This subject was also discussed elaborately in the related subsection. The larger ID extends the premixed mode and therefore the peak in-cylinder pressure, as well as, the temperature was increased. It can be concluded that the prolonged ID period and the availability of the excess amount of oxygen molecules with the addition of isopentanol cause a higher amount of NO_X formation. Additionally, the lowest results were obtained with the infusion of isopropanol. This is maybe owing to the higher LHV, lesser calorific value, higher oxygen content, and lesser CN of the isopropanol. Kumar and Saravanan [36] stated that the NO_X emission was higher for long-chain alcohol/diesel fuel blends comparatively because of raising in the LHV and CN of the blend. It can be accomplished that the outcomes for the NO_X emission coming from this study also in accordance with the previously conducted research reports [67, 97, 98].

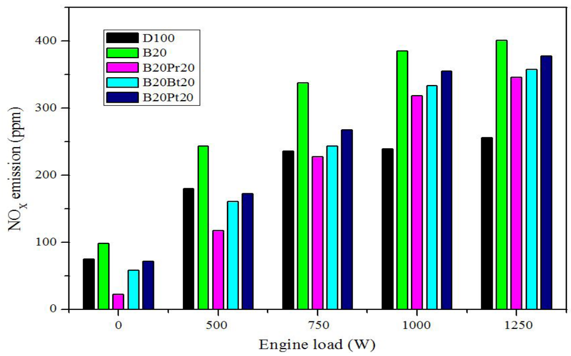

Figure 7. Change of NO_X emissions against the engine load

3.2.4. Carbon monoxide emission

One of the most hazardous exhaust gases that immediately influences the people as well as the environment is the CO emission and it implies the incomplete combustion process [98]. Thus, it is taken to the account as a substantial space in the emission regulation all over the world. The inappropriate injection of fuel inside the cylinder, burning in the shortage of oxygen situations or rich air-fuel mixture are the major features that lead to the formation of CO emission in the cylinder [73]. The variation of CO emission for the used fuel samples in this study according to the load is shown in Fig. 8. Even though the CO emissions of the tested fuels increased with the increase in the load, the figures up to 750 W operating conditions were observed almost similar. This is a common trend for this type of engine that has been monitored in all fixed speed CI engines for different alternative fuel samples as well [99]. This is may be due to the engine is operating with a leaner air/fuel mixture at the lower loads and the attendance of much more fuel at the highest loads causes to the generation of more fuel-rich regions inside the cylinder [84]. It is evident from Fig. 8 that the petroleum-based diesel fuel released more CO emission at all engine load in comparison with the B20 fuel. This can be briefly explained as the native characteristics of the COME since biodiesel fuels are an oxygenated fuel additive and they have approximately 10-12% oxygen content in their chemical bonds whereas conventional diesel fuel is a mineral petroleum product and consists of the pure hydrocarbon chain [88, 100]. At 1250 W, the CO emissions for D100, B20, B20Pr20, B20Bt20, and B20Pt20 were found to be at 1.31%, 1.09%, 1.39%, 1.52%, and 1.66%, respectively. As seen, the supplementation of alcohol to the diesel/biodiesel blend led to increasing CO emission drastically. This can be mainly because of the longer ID duration resulting from the addition of alcohol. The alcohols have a lower CN (as presented in Table 1) which leads to an increase in the ID period. In other words, a large number of fuel accumulates in the combustion chamber because of lower CN of fuel. Hence, a lot of fuel-rich places in the cylinder occurs resulting, in turn, raise the CO emission [8]. Furthermore, another reason is the elevated LHV of alcohol. This case leads to becoming a quenching impact in the combustion chamber which helps to decrease the temperature of the cylinder resulting in the getting worse the combustion efficiency [52, 101]. When Fig. 8 was evaluated, the isopentanol added fuel sample release more CO emission from the exhaust. This is due to the number of carbon atoms in the chemical structure of alcohol. Table 1 presents the carbon numbers of the alcohols. Namely, the increase in the carbon content of the alcohol put across becoming a higher amount of CO emission formation in accordance with the B20. In addition, the achieved results have been consistent with the previous researches [102, 103]

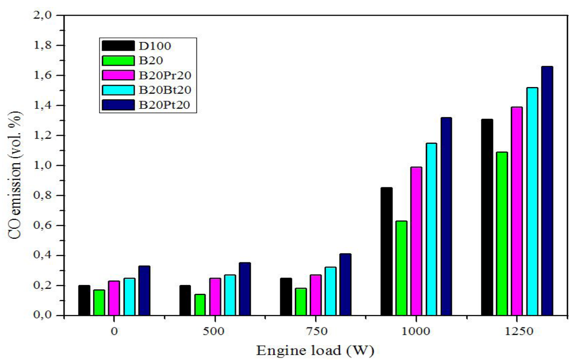

Figure 8. Change of CO emissions against the engine load

3.2.5. Smoke opacity

Smoke opacity, the only visible exhaust gas, is a characteristic that performs the optical properties of exhaust gases of diesel engines. The main reason for the formation of smoke opacity is that large-sized fuel particles forming the fuel-rich places inside the chamber of combustion cause the formation of unburned fuel particles in the exhaust gases [73]. In this direction, the change of smoke opacity results for the tested fuel samples against the several loads is represented in Fig. 9. It is to be noticed from the graph that the smoke opacity is in turn raised with the rise of the engine load for all the tested fuels. Moreover, the maximum figures were observed at the peak load of 1250 W. It is seen that D100 generated the utmost smoke intensity results among the tested fuels at entire the loads. When the tested CI engine run on the biodiesel fuel blend, the smoke opacity values dropped at all loads and the outcomes are good agreement with the conducted experiments from various researchers [104, 105]. The main reason for this trend is the capability of fine combustion process resulting in the reduction of the smoke opacity. It is noteworthy to notice that the smoke opacity results for all the tested ternary alternative blends were lesser than those of pure D100 and B20. At 1250 W, the smoke opacity values for D100, B20, B20Pr20, B20Bt20, and B20Pt20 were found to be at 74.0%, 72.0%, 71.2%, 70.5%, and 69.6%, respectively. As appeared, the addition of alcohols having various chain lengths led to mitigating the smoke opacity strictly with respect to the D100. Accordingly, this is due to the wealth of the native oxygen concentration of the alcohols which may result in smoke emission decreasing [102]. Remarkably, the smoke opacity for the isopropanol blend is slightly lower than that of the B20 blend at the maximum engine load. This might be grounded to the course of the isopropanol being somewhat chain length that means include much more oxygen molecules in its structure than the others leading to becoming a cooling effect inside the cylinder. The opposite of this situation can be clearly said to occur with isopentanol. Kumar et al. [37] have indicated that the smoke opacity for a CI engine might be rearranged thanks to using long-chain alcohol infusion as a fuel additive.

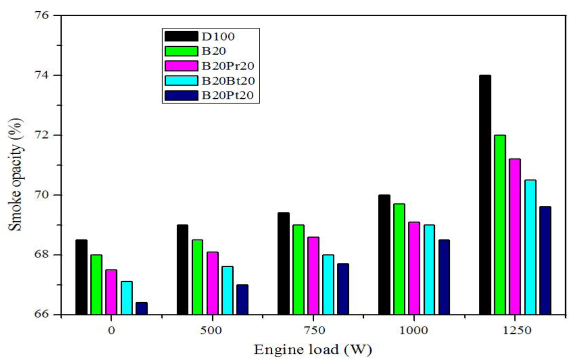

Figure 9. Change of smoke emissions against the engine load

CONCLUSION

In the present experimental research, a comprehensive study has been conducted on in a single-cylinder, four-stroke, naturally-aspirated, DI diesel engine using higher-

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order alcohols like isopropanol-C3, 1-butanol-C4, and isopentanol-C5 as alternative fuel additives with D100 and COME as ternary blends at various engine loads (0, 500, 750, 1000, and 1250 W) and a constant engine speed. The concentration of alcohol, as well as biodiesel, was maintained to be 20% since obtaining stable engine operation during the experimentations. Moreover, the physicochemical characteristics of these prepared ternary blends set out that they could be utilized as alternative fuels in the CI engine when blended with COME and diesel fuel. Based on the experimental investigation, the following conclusions are found.

- BTE of ternary blends is lower than those of D100 and B20 due to the lower calorific value of alcohol. The BTE outcomes increased with the addition of higher-order alcohols in terms of the increase in the number of the carbon atoms, and hence, 20% isopentanol exhibits the highest BTE by 20.36% among the ternary blends.

- On the other hand, BSFC for the tested ternary blends is found to be higher than those of pure D100 and B20 fuel blend because of the aforementioned reason. In contrast to the BTE inclination, BSFC is observed to be the utmost for B20Pr20 among all the tested fuels. It implies that with the usage of higher carbon chained alcohol in the mixture, BSFC reduces on account of the higher net calorific value of long-chain alcohols.

- As far as the EGT results are taken into consideration, the maximum EGT values for D100, B20, B20Pr20, B20Bt20, and B20Pt20 at the maximum load were noted to be as 298°C, 263°C, 234°C, 244°C, and 256°C, respectively. A lower energy content resulting in lower heat energy and higher LHV leading to decrease cylinder temperature due to the quenching effect caused to decrease the EGT when the test engine fuelled with the alcohol-infused alternative fuel blends.

- The unburned HC and smoke opacity emissions for the ternary blends were concerned, it is to be noted that there is a sharp decrement due to the addition of higher alcohols having elevated inherent oxygen molecules in their molecular structures resulting in improved fuel atomization characteristics.

- The CO_2 emissions for D100, B20, B20Pr20, B20Bt20, and B20Pt20 at 1250 W engine load were determined to be as 7.15%, 7.42%, 8.64%, 9.00%, and 10.33%, respectively.
- During the experimentation, the reduction in the NO_X emissions for B20Pr20, B20Bt20, and B20Pt20 at all loads with respect to the B20 blend were recorded, but, the results still higher than that of pure D100.

Overall, it can be accomplished that the addition of higher-order alcohol like isopropanol, 1-butanol, and isopentanol as fuel additives with diesel/COME may be assessed as the potential alternative fuel blends for the CI engine application. However, many kinds of research are necessary to be performed in long term usage in present engines such as vehicle engines, diesel generator, etc. prior to the considering as a commercial meaning.

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