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Effect of biodiesel-dimethyl carbonate blends on engine performance, combustion and emission characteristics

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Combustion characteristics

Abstract Present study investigates the effect of palm biodiesel blends with and without oxygenated alcohol dimethyl carbonate (DMC) on compression ignition engine. H_2SO_4 was used to treat the crude palm oil. Furthermore, acid treated palm oil was converted into palm biodiesel via ultrasound-assisted transesterification process at operating conditions of catalyst (KOH) concentration of 0.75 wt%, methanol to oil ratio of 60 V/V %, reaction time of 38 min, reaction temperature of 60 °C and 59% duty cycle. The antioxidant used in biodiesel blends was dimethyl carbonate. These samples were prepared by adding DMC 10% by volume into biodiesel blends at stirring speed of 2000 rpm for 30 min in order to make a homogenous blend. The key fuel prop-

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Abbreviations: BSFC, Brake specific fuel consumption; BTE, Brake thermal efficiency; BP, Brake power; CI, Compression ignition; CO, Carbon monoxide; CO_2, Carbon dioxide; DI, Direct injection; EGT, Exhaust gas temperature; FAC, Fatty acid composition; GC, Gas chromatography; HC, Hydrocarbon; HCN, Hydrogen cyanide; HRR, Heat release rate; MHRR, Maximum heat release rate; NOx, Oxides of nitrogen (NO, NO2); PME, Palm methyl ester; SOC, Start of combustion; EOC, End of combustion

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erties of the six fuel samples before being engine tested were measured including kinematic viscosity, dynamic viscosity, density, flash point, acid value and calorific value. Engine performance, emission and combustion characteristics were investigated by operating engine at full load condition and varying engine speeds from 1100 rpm to 2100 rpm. Major findings were average increase of 1.70%, 1.22% and 0.95% in BP; average decrease of 1.31%, 2.93% and 1.08% in BSFC; average increase of 4.30%, 4.77% and 4.90% in BTE; average decrease of 2.63%, 2.80% and 4.54% in EGT; significant reduction of 19.04%, 25% and 26.47% in CO emissions; average reduction of 12.76%, 19.35% and 33.33% in HC emissions observed for B10 + DMC, B20 + DMC and B30 + DMC as compared to biodiesel blends without antioxidant.

1. Introduction

Industrialization is increasing day by day because of population increment ultimately increasing global energy demand [1]. In order to cater the increment of global energy demand, more resources are required to harness energy [2–4]. Basically, there are two main types of energy harnessing resources namely renewable and non-renewable energy resources [5]. Currently, most of the energy requirement is fulfilled via non-renewable energy resources utilization [6]. Fossil fuels being non-renewable energy resources are mostly utilized for energy production [7]. According to statistics, 40% fossil fuels utilization increment is predicted by 2025 [8]. Energy utilization is increased by 1.4% from 2013 to 2018. Transportation sector utilized almost 33% of total energy consumption from 2017 to 2018 and almost 95% of transport sector energy demand is fulfilled via fossil fuels utilization [9]. More consumption of fossil fuels means more greenhouse gas emissions [10]. One fourth of these harmful greenhouse gas emissions is because of transport sector [11–13]. For the sake of this colossal issue resolution, some alternative energy resources are required. Discovering alternative energy resources is key importance for researchers to reduce harmful emission effects [14].

In order to mitigate emission related hazards, alternative biofuels have increased researchers inquisitiveness because of enhanced acceptable thermophysical, emission and performance characteristics [15,16]. Transesterification is utilized for biodiesel production via Fatty acid and alcohol esters [17]. Some homogeneous catalysts like KOH, NaOH, and CH_3ONa are also employed during transesterification [18–20].

Biodiesel and biodisel blends along with diesel can be utilized in compression ignition engines with no or little enhancements [21]. Biodiesel yield is produced biodiesel from transesterification having operational constraints dependency [22,23]. Temperature, catalyst concentration, methanol to oil ratio, reaction speed and reaction time are operational constraints [24]. In order to obtain FAME's maximum yield, operating constraints optimization is necessary [25]. Biodiesel characterization is also a key constituent to consider in order to obtain elemental analysis of biodiesel [26]. The amounts of glycerol, ester, unreacted triglycerides and some other constituents have been analyzed. GCMS, HPLC and NMR spectroscopy are some of the methodologies which are employed for biodiesel's characterization [27]. There are different parameters which affects the performance of compression ignition (CI) engines like high compression ratio, higher injector opening temperature and advance injection opening time [28–30]. Upon biodiesel testing on 6-cylinder diesel engine, minor decrement of BT and BTE was observed [19]. CO and CO_2 emissions reduction was noticed along with NO_x upsurge while utilization of biodiesel blends [31,32]. Ruhul et al. [33] investigated CI engine's performance and emission scenarios via utilizing croton-megalocarpus and millettia pinnata biodiesel blends. Consequently, 18.46% decrement of CO and 9% decrement of HC emissions was examined while there was an increment of 8.16% of NO_x emissions was observed. There was an engine performance decrement while utilizing biodiesel blends regarding pure diesel utilization [34]. Sanjid et al. [35] utilized kapok-moringa mixed blends of biodiesel in compression ignition engines for performance and emission analysis. 6–9% increment of BSFC and 17% of NO_x was noticed while there was a decrease of 23% and 16% for HC and CO accordingly relative to diesel. Sinha et al. [36] took waste cottonseed oil for production of biodiesel and examined its blends via compression ignition engine. Consequently, 26.04% BTE and 0.32 kg/kWh BSFC was obtained by utilizing full load condition for B10. Also, CO and HC emission decrement and slight increment of NO_x was observed. In order to control emissions and to optimize performance at the same time, researchers are employing some techniques like ternary biodiesel blends, exhaust gas reduction (FGR), engine design and fuel preparation modification and utilizing some additives generally nano additives in biodiesel [37–40].

Because of poor cold flow characteristics of biodiesel, some issues aroused like incomplete combustion, fuel starvation and filter clogging during winters [41]. Mujtaba et al. [42] analyzed that cold flow characteristics of palm oil can be optimized by blending it with highly saturated feedstock like sesame oil. It was noticed that mixing of palm oil and sesame oil can enhance oxidation stability according to ASTM and EN standards. Presently, liquid (oxygenated alcohols) and solid (nanoparticles) additives are captivating interest of researchers [43–45]. In compression ignition engines, alcohol utilization is not as simple because of fragile lubricating characteristics, less cetane number and high auto-ignition temperature [46].

Many researchers have examined oxygenated alcoholic fuel as an additive for diesel engines [12,47,48]. The characteristics of diethyl ether (DEE) like high oxygen content, high volatility, non-corrosive etc. are promising [49]. DEE also have high heating value relative to butanol [50]. By utilizing DEE engine performance was enhanced. 7.2% increment of BTE and 6.7% of BSFC reduction was noticed comparative to pure diesel [21]. Venu *et al.* [51] utilized DEE along with diesel in simple diesel engine and varies the DEE concentration (5–12.5%).

Utilizing 100% engine load, ternary blends demonstrated good harmful emissions decrement like NO_X by 57%, CO by 4.6% and HC by 84% [52]. 53.3% oxygen is present in dimethyl carbonate (DMC) among oxygenated alcohol fuels [53]. Combustion enhancement was noticed because of oxygen interaction with C-C bond to generate CO. DMC is almost 15% miscible in pure biodiesel relative to methanol and ethanol. Also, there is a requirement of surfactants or solvents in case of methanol and ethanol to attain stable alcohol-diesel blend with no phase separation [54]. Pan *et al.* [53] investigated DMC influence in CI engine. 10% DMC exhibited good BTE relative to pure diesel. 80% soot emission decrement was observed with 20% DMC blend.

As far as present research is concerned, there is a palm oil utilization for the sake of biodiesel production via ultrasound-assisted transesterification. Main aim is to examine 10% DMC effect regarding 3 blends like B10, B20 and B30 on engine performance, emissions and combustion characteristics. DMC contains 53% oxygen in its chemical structure, which assisted to improve the combustion process and resulted in better diesel engine performance and emission characteristics. For this current study, ultrasound assisted technique is used for production of palm biodiesel due to cost, energy, and time efficient.

2. Materials and methods

2.1. Materials

The palm oil was bought from Pakistan's local marketplace. High speed diesel, and other chemicals including methanol, sulfuric acid, KOH, dimethyl carbonate (DMC) were attained from the local vendors. Chemicals utilized in this research were of analytical grade.

2.2. Biodiesel production and characterization

Transesterification process was utilized for crude palm oil processing in order to attain palm biodiesel. Before conversion of palm oil into palm biodiesel the acid value of palm oil was checked, the acid value of crude palm oil was 2.8 mg KOH/g (i.e., the FFA value of 5.6%) which was not appropriate for biodiesel production through transesterification process. Sahar et al. [55] investigated that FFA value of any oil greater than 1% and 2 mg KOH/g acid value are not suitable for production of biodiesel. Acid value has been reduced in a process known as acid esterification process. Mineral acid H_2SO_4 and methanol were used along with other operating parameters of reaction speed of 500 rpm, reaction temperature 57 °C, and reaction time of 2 h. The quantity of methanol in acid esterification process plays an important role, the quantity of methanol has been selected as 2.25 × FFA, and H_2SO_4 as 0.05 × FFA.

Aid value and FFA value of palm oil were determined using **Equation** (1) &(2) [19].

$$AcidValue = \frac{56.1 \times N \times V}{W} \tag{1}$$

$$FFA = \frac{Acid\ \ Value}{2} \tag{2}$$

where N represents KOH normality, V represents KOH volume and utilized palm oil weight is represented by W. Also, distilled water was employed for titration purpose.

Two steps acid esterification process was employed. In first step, palm oil acid value was decreased by 1.345 and further reduced in second step up to 0.339. The acid treated palm oil was converted into palm biodiesel via ultrasound-assisted transesterification process at operating conditions of catalyst

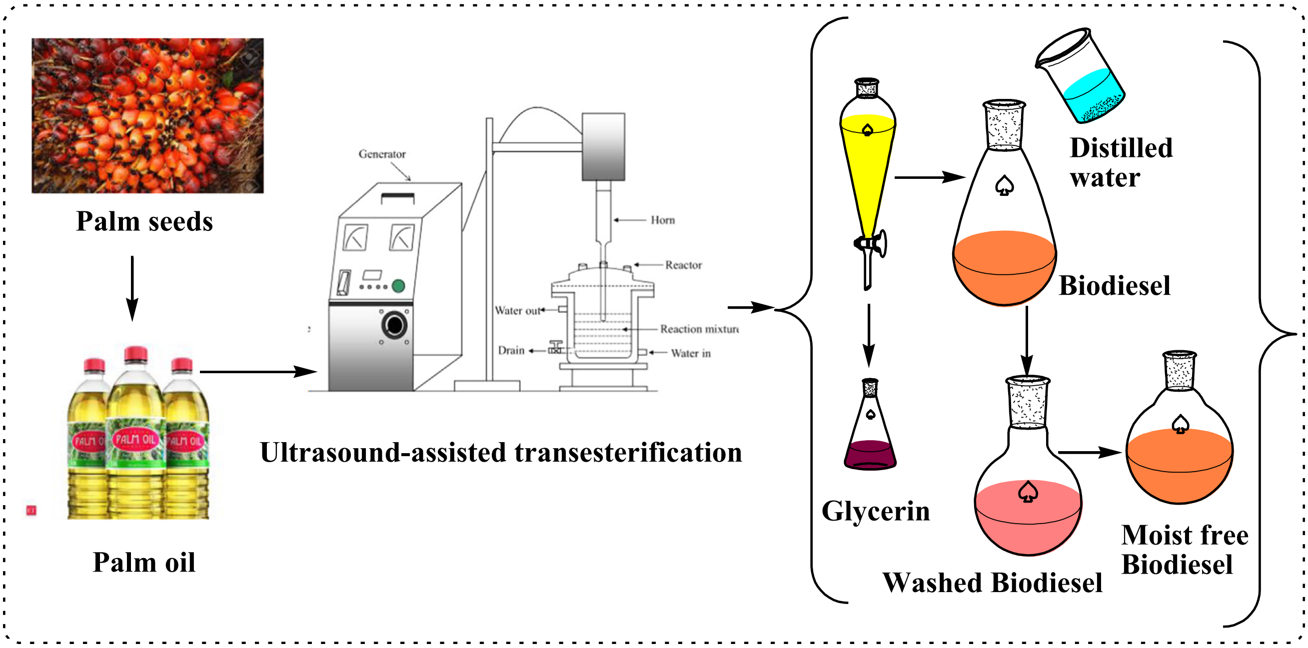

Fig. 1 Schematic diagram of whole procedure for palm biodiesel production.

(KOH) concentration of 0.75 wt%, methanol to oil ratio of 60 V/V %, reaction time of 38 min, reaction temperature of 60 °C and 59% duty cycle. The schematic diagram of whole process is demonstrated in Fig. 1. Utilized catalyst amount of transesterification process has been calculated via **Equation (3)** [19].

$$Amount\ \ catalyst\ \ used = \frac{Catalyst\ \ concentration \times weight\ \ of\ \ palm\ \ oil\ \ used}{100} \tag{3}$$

Homogenous catalyst KOH mixed with methanol and then poured into acid treated palm oil and reaction was started at given operation parameters. On reaction completion, mixture was poured to separating funnel and left for 10 h to settle down the impurities present in the mixture. Mixture was divided in to two layers; upper layer was biodiesel and lower layer was glycerin. The lower layer has been removed from the separating funnel and remaining biodiesel was washed via hot distilled water for remaining impurities eradication. Water content was removed via rotary evaporator and methanol impurities from washed biodiesel. At the end, Whatman filter paper was used to eradicate any traces of catalyst present in evaporated biodiesel. Biodiesel yield has been recognized as an important factor and it can be calculated using **Equation (4)** [19].

$$Biodiesel\ \ yield = \frac{Quantity\ \ of\ \ biodiesel\ \ produced}{weight\ \ of\ \ palm\ \ oil\ \ used} \times 100 \tag{4}$$

Gas chromatography mass spectrum (Agilent 7890, USA) technique was employed for palm biodiesel composition determination. GCMS analysis showed palm biodiesel consist of long chain fatty acids methyl esters as mentioned in Table 1.

2.3. Biodiesel blends

Six biodiesel blends were prepared for the analysis of performance, emission and combustion characteristics of diesel engine. Among these six blends three blends were B10, B20, B30 without antioxidant while other three blends are with antioxidant. The antioxidant used in biodiesel blends was dimethyl carbonate. These samples were prepared by adding DMC 10% by volume into biodiesel blends at 2000 rpm stirring speed for 30 min to make a homogenous blend. Important fuel properties of six fuel samples prior to engine testing were measured like kinematic viscosity, dynamic viscosity, density, flash point, acid value and calorific value and shown in Table 2.

2.4. Engine setup

These biodiesel blends were tested via water cooled single cylinder diesel engine. Schematic diagram of utilized diesel engine is exhibited in Fig. 2 while technical specifications of this engine are mentioned in Table 3. Engine was operated via pure diesel initially to attain steady state condition. After that, biodiesel blends were utilized to analyze engine performance characteristics. Fuel flow rate has been quantified by ascribing a graduate measuring cylinder along with fuel tank. Engine performance characteristics including brake power, brake specific fuel consumption, brake thermal efficiency and exhaust gas temperature, emission characteristics including carbon monoxide, unburned hydrocarbon and nitrogen oxide and combustion characteristics including in-cylinder pressure and heat release rate were investigated. Table 4 represented the BOSCH BEA 350 gas analyzer specifications.

Table 1 Composition of long chain fatty acid methyl esters.

Name of FAME	Formula	Structure	% (PME)
Methyl Hexanoate	C5H11COOCH3	C6:0	0.0000
Methyl Octanoate	C7H15COOCH3	C8:0	0.0000
Methyl Decanoate	C9H19COOCH3	C10:0	0.0000
Methyl Laurate	C11H23COOCH3	C12:0	0.2574
Methyl Tetradecanoate	C13H27COOCH3	C14:0	1.0931
Methyl Tetradecanoate	C13H27COOCH3	C14:0	1.0931
Methyl Palmitoleate	C15H29COOCH3	C16:1	0.1503
Methyl heptadecanoate	C16H33COOCH3	C17:0	0.0000
Methyl Octadecanoate	C17H35COOCH3	C18:0	4.3144
Methyl oleate	C17H33COOCH3	C18:1	41.3787
Methyl Linoleate	C17H31COOCH3	C18:2 (CIS)	7.7571
	C17H31COOCH3	C18:2 (ISOMER)	

Table 2 Physiochemical characteristics of biodiesel blends.

Property	Unit	B10	B20	B30	B10 + DMC	B20 + DMC	B30 + DMC
Kinematic viscosity @ 40° C	mm^2/s	3.4270	3.4323	3.4521	3.4323	3.4589	3.4602
Dynamic viscosity @ 40° C	mPa.s	2.8475	2.8816	2.9123	2.8513	2.8912	2.9365
Density @ 15 °C	g/cm^3	0.8296	0.8338	0.8457	0.8311	0.8433	0.8492
Flash Point	C	98.5	105.5	115.5	100.5	114.5	119.5
Acid value	mgKOH/g	0.1122	0.1383	0.1675	0.1825	0.1938	0.2533
Calorific value	kJ/kg	44,537	43,278	42,582	44,785	43,585	42,663

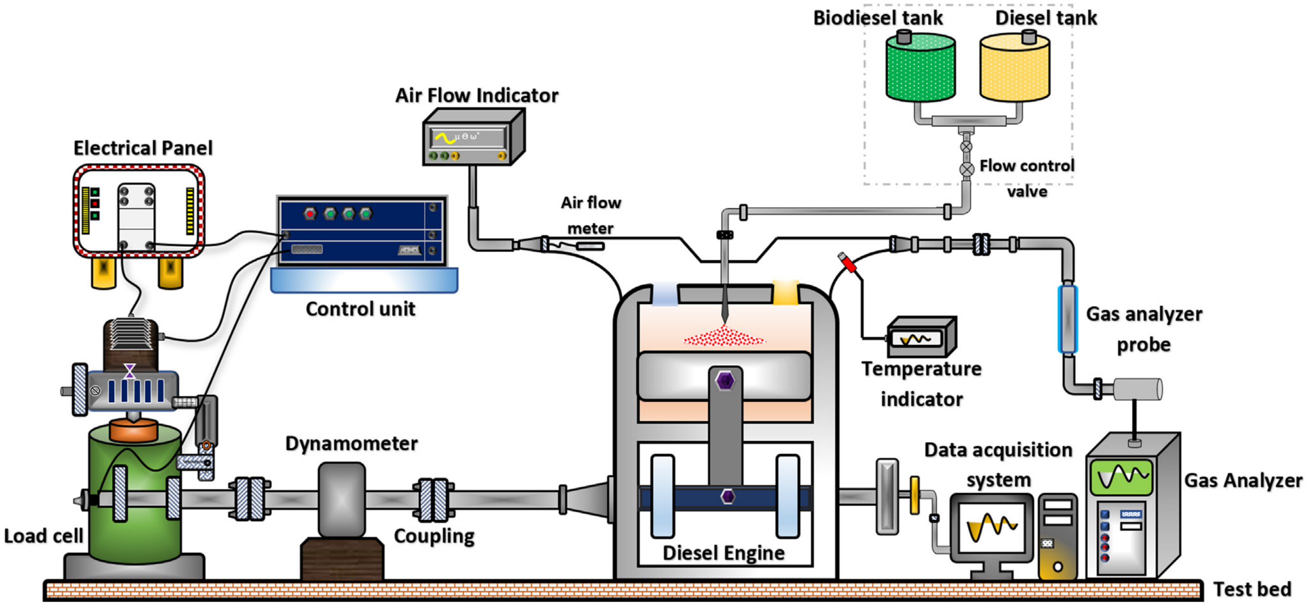

Fig. 2 Schematic diagram of compression ignition engine.

Table 3 Specification of compression ignition engine.

No.	Description	Specifications	No.	Description	Specifications
1	No of cylinders	1	5	Compression ratio	17.7
2	Displacement	0.638 L	6	Maximum power	7.7 kW
3	Bore	92 mm	7	Maximum engine speed	2400 rpm
4	Stroke	96 mm	8	Cooling system	Radiator cooling

Table 4 Specifications of exhaust gas analyzer.

Equipment	Method	Measurement	Accuracy
BOSCH BEA 350	Non-dispersive infrared	CO	±0.02 vol%
	Flame ionization detector (FID)	HC	±1 ppm
	Heated vacuum type chemiluminescence detector (CLD)	NOx	±1 ppm

3. Result and discussion

3.1. Engine performance

3.1.1. Brake power

Fig. 3 demonstrates variation of brake power at different engine speeds and full load condition. It has been examined that there is a brake power increment by increasing engine speed from 1100 rpm to 2100 rpm. The maximum brake power of 7.12, 7.17, 7.23, 7.24, 7.25 and 7.26 kW were chronicled at 2100 rpm for B10, B20, B30, B10 + DMC, B20 + DMC and B30 + DMC respectively. Biodiesel blends without DMC showed lower brake power as compared to other blends with DMC. This decrement is because of lower calorific value. Lower calorific value means less energy will be released after combustion, and higher viscosity means higher resistance in fuel line for pump line nozzle system which leads to higher delay in tart of injection as well as poorer fuel atomization. Hence, these two reasons cause lower power output [56]. 10% antioxidant dimethyl carbonate was added into three blends (B10, B20 and B30). It has been observed that sample with antioxidant showed slightly higher brake power compared to that of no addition of antioxidant. The average increase in brake power for B10 + DMC, B20 + DMC and B30 + DMC were 1.70%, 1.22% and 0.95% respectively compared to each of the sample without addition of antioxidant. This brake power increment is because of antioxidant which improves calorific value of PME blends. The ignition delay period also increased by adding DMC in biodiesel blends enhancing combustion process due to lower cetane number of oxygenated biodiesel blends. As ignition delay time depends

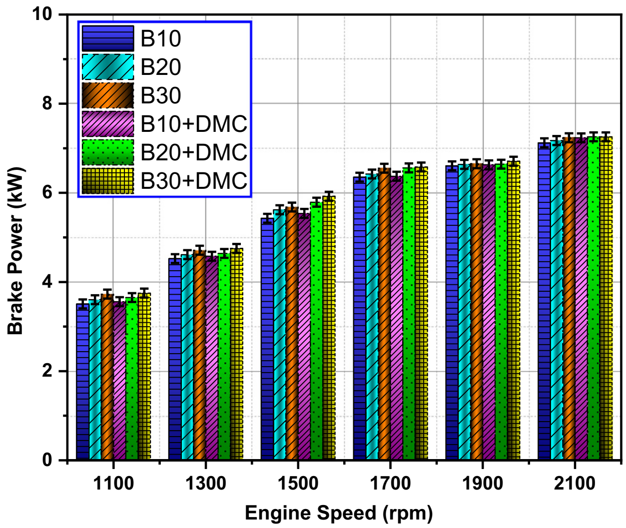

Fig. 3 Variation in brake power for biodiesel blends with varying engine speed.

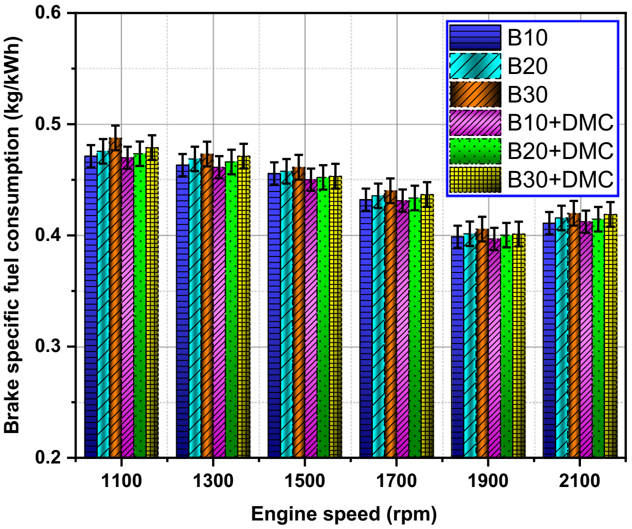

Fig. 4 Variation in BSFC of biodiesel blends at varying engine speeds.

upon cetane number and latent heat of vaporization of tested blends [57].

3.1.2. Brake specific fuel consumption

Fig. 4 shows BSFC variation for PME blends at various engine speeds and full load condition. BSFC is mainly dependent on relationship between volumetric fuel injection system, fuel density, viscosity and energy content [58]. According to observation, BSFC values were more with fuel of higher biodiesel percentage (B30 > B20 > B10). BSFC decreased with engine speed increment up to 1900 rpm then slightly increased at 2100 rpm due to time increment for heat losses from gas to cylinder and piston wall as well. Although, graph shows that BSFC is decreasing along engine speed increment but if the graph is extrapolated then BSFC will increase again with further engine speed increase due to increased friction inside the engine [59]. The minimum BSFC of 0.39876, 0.40145, 0.40567, 0.39678, 0.40021, 0.40121 kg/kWh were found for B10, B20, B30, B10 + DMC, B20 + DMC and B30 + DMC respectively. When DMC antioxidant was added to biodiesel blends, the BSFC was decreased as compared to biodiesel blends without DMC. The average decrease in BSFC of 1.31 %, 2.93 % and 1.08 % were observed for B10 + DMC, B20 + DMC and B30 + DMC respectively compared to each of the blends without antioxidant. Addition of DMC into biodiesel blends improves the calorific value and a lower BSFC. Due to its volatile nature, the mixing of air to fuel mixture also improved with the addition of DMC into biodiesel blends which caused better atomization. The increasing volumetric efficiency reduced work required during the compression stroke causing an enhancement in BSFC of oxygenated biodiesel blends.

3.1.3. Brake thermal efficiency

Fig. 5 represents variation of BTE for PME blends at various engine speeds and full load condition. BTE is heat engine brake power as a function of input heat by fuel. It was observed that as engine speed increase, BTE increases as well but at 2100 rpm a slight decrement in BTE has been observed. It is because of engine's mechanical and frictional losses increment and complete combustion time decrement which means that the consumption rate of fuel is higher. Hence, lower BTE. The maximum values of BTE of 21.54%, 21.32%, 21.09%, 22.51%, 22.39% and 21.99% were obtained for B10, B20, B30, B10 + DMC, B20 + DMC, B30 + DMC respectively at 1900 rpm. The BTE of all three biodiesel blends was improved with the addition of DMC. The average increase in BTE of 4.30%, 4.77% and 4.09% were observed for B10 + DMC, B20 + DMC and B30 + DMC blends comparative to biodiesel blends without DMC additive. With the addition of DMC in biodiesel blends, ignition delay time becomes longer resulted in improvement in BTE. Oxygenated

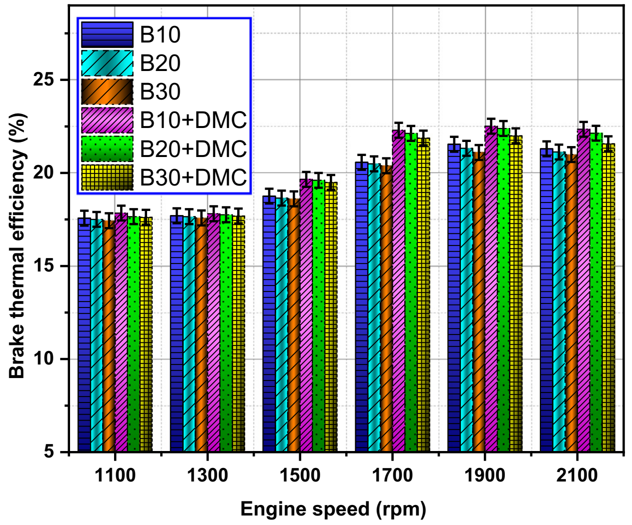

Fig. 5 Variation in BTE of biodiesel blends with varying engine speeds.

alcohols improved the BTE due to petite combustion period and better combustion process [60]. The combustion process in compression ignition engines has been improved with the addition of oxidizing additives, which provided an excess oxygen content into fuel rich zone which rallies the BTE for biodiesel blends. Pan et al. analyzed DMC additive effect with high-speed diesel on BTE of diesel engine and found a major enhancement in BTE and claimed the possible reason behind this complete combustion. Rashedul et al. [61] analyzed three different alcohols including diethyl ether, n-butanol and ethanol additives in biodiesel blends, and compared their effect on BTE of a compression ignition engine and found that the best fuel additive was diethyl ether.

3.1.4. Exhaust gas temperature

Fig. 6 represents EGT variation for PME blends at various engine speeds along with full load condition. Exhaust temperature is critical for combustion process indication and is a key factor of pollutants formation. Physicochemical characteristics including kinematic viscosity, density, cetane number and calorific value have strong influence on EGT. According to observation, EGT values increases for all tested samples with increasing engine speeds. As the concentration of biodiesel increase, EGT tends to increase as well. The average increase in EGT of 9.52% and 13.63% has been observed for B20 and B30 accordingly comparative to B10.

This increment in EGT can be justified, due to high viscosity of biodiesel blends which lead to poor atomization of fuel leading to emergence of unburnt fuel in premixed combustion phase in which they will continue to burn later in the diffusion combustion phase. Hence, combustion of huge fuel amount at one time will lead to higher EGT [62].

The addition of 10% DMC into biodiesel blends improves the EGT. The average reduction in EGT of 2.63%, 2.80% and 4.54% has been observed for B10 + DMC, B20 + DMC and B30 + DMC respectively as compared to biodiesel blends without DMC additive. Lower values of EGT represent the proper burning of biodiesel blends inside the compression ignition engine.

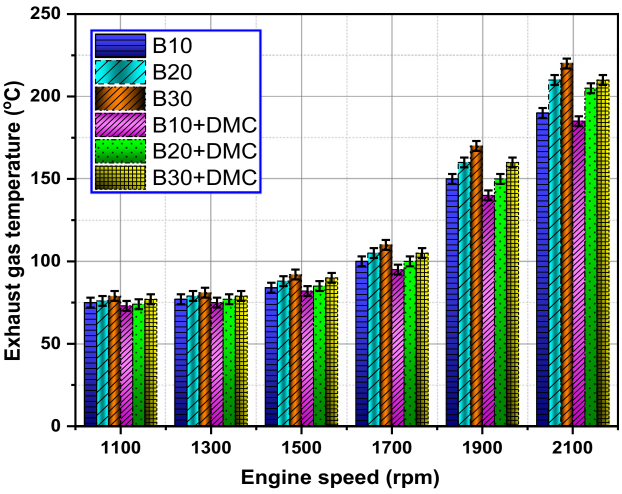

Fig. 6 Effect of engine speed on EGT for different biodiesel blends.

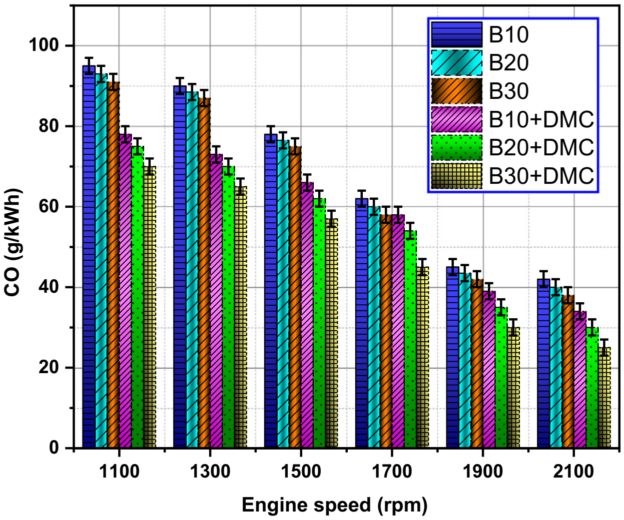

Fig. 7 Effect of engine speed on CO emissions for biodiesel blends with and with fuel additives.

3.2. Emission characteristics

3.2.1. CO emissions

CO is a toxic gas formed when incomplete combustion takes place in an engine when injected with any fuel. Several factors have caused the emission of CO such as engine speed, air–fuel ratio, injection pressure and type of fuel used [63]. Fig. 7 exemplifies CO emission variation when using different types of PME blends at varying engine speed and full load condition. It is observed for all samples that emissions of CO decrease with engine speed increment due to conversion rate increment of CO to CO_2. At high engine speed both air to fuel ratio and combustion temperature inside the cylinder increases which escalates the conversion of CO to CO_2. The CO emissions also reduced with biodiesel concentration increment in biodiesel blends. Minimum values of CO emission for B10, B20, B30, B10 + DMC, B20 + DMC and B30 + DMC were recorded

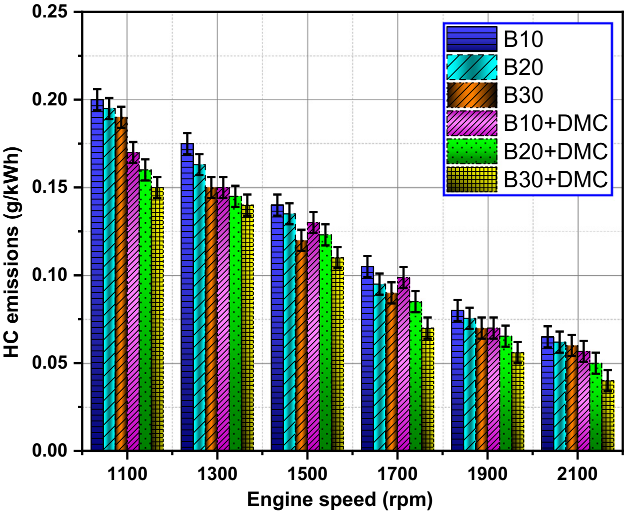

Fig. 8 Effect of engine speed on HC emissions for biodiesel blends with and with fuel additives.

42, 40, 38, 34, 30 and 25 g/kWh at 2100 rpm. The CO emissions further reduced by adding DMC in to biodiesel blends. A significant reduction of 19.04%, 25% and 26.47% in CO emission was observed for B10 + DMC, B20 + DMC and B30 + DMC accordingly comparative to biodiesel blends without DMC. All three biodiesel blends in the presence of DMC showed excellent CO emission decrement because of more oxygen content which leads toward complete combustion. Imtenan et al. [64] investigated the reduction of CO emissions using different oxygenated alcohols as fuel additives. The excess amount of oxygen in biodiesel blends and fuel additives tends the oxidation of CO inside the combustion chamber which results in reduction in CO emissions.

3.2.2. HC emissions

Fig. 8 represents HC emissions variation for different types of PME blends at varying engine speeds and full load condition. HC emissions are dependent of fuel characteristics, engine operating parameters and atomization of fuel [65]. HC emissions have been reduced with increasing engine speed and with increasing biodiesel concentration in biodiesel blends. The minimum values of HC emissions for B10, B20, B30, B10 + DMC, B20 + DMC and B30 + DMC were recorded 0.065, 0.062, 0.06, 0.0567, 0.05 and 0.04 g/kWh respectively at 2100 rpm. Over entire speed range, average reduction of HC emissions for B10 + DMC, B20 + DMC and B30 + DMC were observed 12.76%, 19.35% and 33.33% respectively as compared to biodiesel blends with fuel additives. The main reason behind this significant HC emissions decrement is higher oxygen content of biodiesel and oxygenated alcohol provided some good effect during combustion process such post flame oxidation and higher flame speed which further enhances the oxidation of unburned HC. Hence, resulting in HC emission decrement [66]. Pan et al. [53] analyzed HC emissions decrement via DMC as a fuel additive into biodiesel blends. Major HC emissions decrement was noted. Furthermore, due to high heat release rate and high temperature in combustion chamber unburned hydrocarbons tends to oxidize.

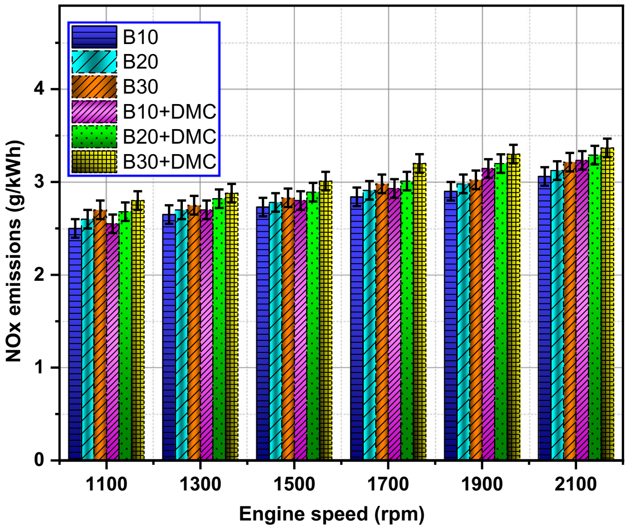

Fig. 9 Effect of engine speed on NO_x emissions for biodiesel blends with and with fuel additives.

3.2.3. NO_x emissions

NO_x emission variations with varying engine speeds from 1100 rpm to 2100 rpm at full load condition have been represented in Fig. 9. The graph revealed an escalation in NO_x emissions with engine speed increment for all tested biodiesel samples with and without fuel additive. Maximum values of NO_x emissions for B10, B20, B30, B10 + DMC, B20 + DMC and B30 + DMC were recorded 3.06, 3.123, 3.213, 3.233, 3.291 and 3.367 g/kWh accordingly at engine speed of 2100 rpm. In-cylinder combustion temperature and pressure are main causes of NO_x formation. The higher temperature and pressure tend to escalate the NO_x emissions. The addition of fuel additive also escalates the NO_x emission to some extent due high cetane number and high oxygen content. Pan et al. [53] utilized DMC as an oxygenated fuel addi-

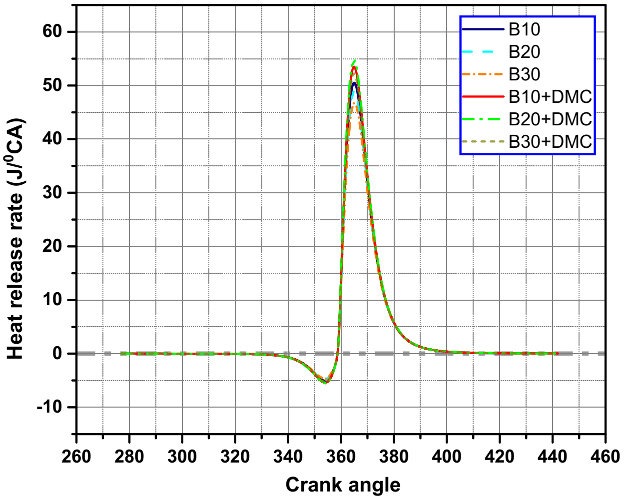

Fig. 10 Variation in heat release rate for different biodiesel blends with and without DMC.

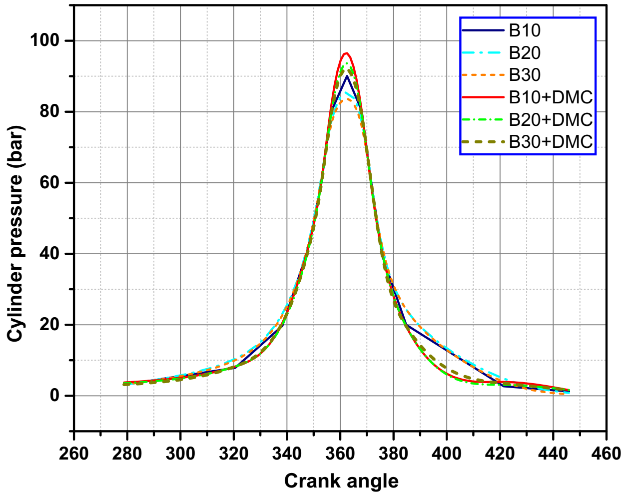

Fig. 11 Variation in cylinder pressure for different biodiesel blends with and without DMC.

tive and observed a considerable upsurge in NO_x emissions and claimed that the reasons behind this escalation are high in cylinder temperature and pressure. Other factor was the higher content of oxygen which leads toward complete combustion of fuel results escalation of in-cylinder temperature causing higher NO_x emissions.

3.3. Combustion characteristics

3.3.1. Heat release rate

Fig. 10 demonstrates Heat Release Rate variation at varying engine speed and full load condition for biodiesel blends with and without antioxidant. The antioxidant used in this test is 10% DMC and is added to three samples (B10, B20 and B30). From the graph data, it has been observed that the sample with addition of antioxidant gives a higher peak heat release rate of 53.92 J/ °CA, 55.26 J/ °CA and 52.66 J/ °CA for B10 + DMC, B20 + DMC and B30 + DMC respectively showing an average increase of 5.52%, 10.67% and 10.40% respectively as compared to B10, B20 and B30. This is because DMC is an oxygenated additive. Hence, it will further improve the calorific value of biodiesel. Since HRR is highly dependent on calorific value of the sample as it is the rate at which combustion process gives out energy, hence the sample with antioxidant will be higher [67]. However, the SOC and EOC of samples added with antioxidant are close to each other. In other words, the combustion duration of the three samples become almost identical to each other after added with 10% DMC. Consequently, antioxidant improved the combustion duration of the sample as well.

3.3.2. In-cylinder pressure

Fig. 11 demonstrates in-cylinder pressure variation at varying engine speed and full load condition for biodiesel blends with and without antioxidant. The antioxidant used in this test is 10% DMC and is added to three samples (B10, B20 and B30). It has been observed that samples with antioxidant added give a higher peak cylinder pressure at 96.3 bar, 94.82 bar and 93.41 bar for B10 + DMC, B20 + DMC and B30 + DMC respectively implying that there is an increment of 5.27%, 5% and 7.05% of each compared to sample without additional antioxidant. The reason to this raise in peak pressure is DMC which is an oxygenated additive increasing the calorific value of PME blends when it is mixed together. Higher calorific value means the amount of heat produced from combustion will be higher as well. Since cylinder pressure is dependent on the combustion stage of fuel, so higher calorific value will also give rise to higher cylinder pressure.

4. Conclusion

Palm oil has been converted into palm biodiesel via ultrasound-assisted transesterification process. The physiochemical characteristics of palm biodiesel were determined according to ASTM standards. Six biodiesel blends including B10, B20, B30, B10 + DMC, B20 + DMC and B30 + DMC were prepared and tested on a compression ignition engine to examine the performance, combustion and emission characteristics by operating the diesel engine at full load condition and varying engine speed from 1100 rpm to 2100 rpm. Results are summarized and given below:

1. Acid treatment of crude palm oil having acid value of 2.8 mg KOH/g was accomplished in two steps; in first step the acid value of palm oil reduced up to 1.345 mg KOH/g and further reduced in second step up to 0.339 mg KOH/g. The operating conditions of ultrasound-assisted transesterification process was kept as catalyst (KOH) concentration of 0.75 wt%, methanol to oil ratio of 60 V/V %, reaction time of 38 min, reaction temperature of 60 °C and 59% duty cycle. 10% dimethyl carbonate antioxidant has been added into different biodiesel blends.
2. The average increase in brake power for B10 + DMC, B20 + DMC and B30 + DMC were 1.70%, 1.22% and 0.95% respectively compared to each of the sample without addition of antioxidant. The average decrease in BSFC of 1.31 %, 2.93 % and 1.08 % were observed for B10 + DMC, B20 + DMC and B30 + DMC respectively compared to each of the blends without antioxidant. The average increase in BTE of 4.30%, 4.77% and 4.09% were observed for B10 + DMC, B20 + DMC and B30 + DMC blends as compared to biodiesel blends without DMC additive.
3. A significant reduction of 19.04%, 25% and 26.47% in CO emission was observed for B10 + DMC, B20 + DMC and B30 + DMC respectively as compared to biodiesel blends without DMC. The average reduction of HC emissions for B10 + DMC, B20 + DMC and B30 + DMC were observed 12.76%, 19.35% and 33.33% respectively comparative to biodiesel blends with fuel additives.
4. Average increase of 5.52%, 10.67% and 10.40% in heat release rate has been observed for B10 + DMC, B20 + DMC and B30 + DMC accordingly as comparative to B10, B20 and B30. The average reduction in EGT of 2.63%, 2.80% and 4.54% has been observed for B10 + DMC, B20 + DMC and B30 + DMC respectively as compared to biodiesel blends without DMC additive. Maximum peak cylinder pressure of 96.3 bar, 94.82 bar and 93.41 bar were observed for B10 + DMC, B20 + DMC and B30 + DMC respectively.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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