

Article

Comparative Assessment of Spray Behavior, Combustion and Engine Performance of ABE-Biodiesel/Diesel as Fuel in DI Diesel Engine

Sattar Jabbar Murad Algayyim ^{1,2,3,*}  and Andrew P. Wandel ² 

¹ Department of Mechanical Engineering, University of Al-Qadisiyah, Al-Diwaniyah 58001, Iraq

² School of Mechanical and Electrical Engineering, University of Southern Queensland, Toowoomba 4350, Australia; andrew.wandel@usq.edu.au

³ Al-Diwaniyah Water Department, Al-Diwaniyah Governorate, Al-Diwaniyah 58001, Iraq

* Correspondence: sattarjabbarmurad.algayyim@usq.edu.au or ialiraq12@yahoo.com; Tel.: +61-431-291-580

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Abstract: This study investigates the impact of an acetone-butanol-ethanol (ABE) mixture on spray parameters, engine performance and emission levels of neat cottonseed biodiesel and neat diesel blends. The spray test was carried out using a high-speed camera, and the engine test was conducted on a variable compression diesel engine. Adding an ABE blend can increase the spray penetration of both neat biodiesel and diesel due to the low viscosity and surface tension, thereby enhancing the vaporization rate and combustion efficiency. A maximum in-cylinder pressure value was recorded for the ABE-diesel blend. The brake power (BP) of all ABE blends was slightly reduced due to the low heating values of ABE blends. Exhaust gas temperature (EGT), nitrogen oxides (NO_x) and carbon monoxide (CO) emissions were also reduced with the addition of the ABE blend to neat diesel and biodiesel by 14–17%, 11–13% and 25–54%, respectively, compared to neat diesel. Unburnt hydrocarbon (UHC) emissions were reduced with the addition of ABE to diesel by 13%, while UHC emissions were increased with the addition of ABE to biodiesel blend by 25–34% compared to neat diesel. It can be concluded that the ABE mixture is a good additive blend to neat diesel rather than neat biodiesel for improving diesel properties by using green energy for compression ignition (CI) engines with no or minor modifications.

Keywords: acetone-butanol-ethanol mixture; biodiesel; spray visualization; emissions

1. Introduction

The rapid depletion of fossil fuel reserves, population growth and the increase in air pollution from internal combustion engines using fossil fuels have motivated the search for an alternative biofuel such as biodiesel and alcohol [1,2]. Acetone-butanol-ethanol (ABE), a butanol intermediate product fermentation, has shown potential as an additive fuel blend for conventional diesel due to a reduction in the recovery cost requirements of butanol separation [3–5]. Another benefit of using ABE is that it is produced from renewable sources such as agricultural waste [6–8]. Furthermore, a variety of biomass types can be used as a source of ABE fermentation [3].

The ABE blend has attracted researchers' attention because it is a renewable fuel that reduces dependence on fossil fuels and decreases diesel engine emissions [9,10]. Researchers have experimentally tested ABE mixtures with several investigations [11,12] assessing ABE blend performance under different operating conditions. Luo et al. [13] investigated the sooting tendency of ABE fuels blended with diesel. They found that ABE-diesel has a lower sooting tendency than the butanol-diesel blend because it possesses higher oxygen content and lower carbon content for the same blend ratio.

Ma et al. [14] tested droplet evaporation of an ABE blend. The ABE mixture addition enhanced the droplet evaporation speed, and thus reduced the droplet lifetime. Therefore, droplet clouds have a significant impact on the propagation of turbulent flame. The pre-evaporation rate and droplet size are important parameters in controlling burning velocity. Droplet size and the overall number of droplets also have a substantial impact on ignition success, so the high evaporation rate resulting from the additions of an ABE mixture could improve combustion rates [15]. Recently, a study [16] investigated the impact of a butanol-acetone (BA) mixture as an additive for biodiesel fuel on spray and combustion characteristics. The experimental results revealed that all BA mixtures enhanced spray penetration, offered some improvement in brake power and reduced emission levels (UHC, CO and NO_x). The abovementioned studies support the advantages of using ABE in compression ignition (CI) engines [3,17,18]. Recent research by the authors [5] has also investigated ABE-diesel blends and found that the studied ABE blend reduced exhaust emissions.

To the best of our knowledge, comparative assessment of the ABE mixture as an additive to neat biodiesel (cottonseed) and neat diesel, and the related spray characteristics and engine performance, have not been fully studied. The main goal of this paper is to evaluate and compare the macroscopic spray parameters and engine performance of 10% ABE blended with neat biodiesel and diesel as fuel in a direct injection (DI) diesel engine.

2. Materials and Methods

2.1. Fuel Preparation

Cottonseed biodiesel was prepared from cottonseed oil via transesterification. The fatty acid compositions of the cottonseed biodiesel (chemical profiles) were determined using Flame Ionization Detector-Equipped Gas Chromatography (FID-GC) [19]. The analytical grades of normal butanol (nB) and acetone (A) were used with 99.8% purity, and ethanol was used with 100% purity. All alcohol blends were obtained from Chem-Supply Australia. The ABE blend was mixed with a ratio of A:B:E (3:6:1) by volume and used to simulate ABE fermentation [3]. ABE (10%) was blended with 90% neat cottonseed biodiesel (Bd), which is referred to as ABE10Bd90. ABE (10%) was also blended with 90% neat diesel (D) creating ABE10D90. Blend density was measured according to ASTM 1298 [20,21]. The blends' dynamic viscosities were measured according to the ASTM 445-01 [22] using a Brookfield Viscometer (DV-II+Pro Extra, AMETEK Brookfield, Middleboro, MA, USA). The kinematic viscosity was then calculated [23]. The blends' calorific values were measured using a digital oxygen bomb calorimeter (XRY-1A, Shanghai Changji Geological Instrument Co., Ltd., Shanghai, China) following ASTM D240 [24,25]. The properties of the neat fuel are listed in Table 1, and the measured blends' properties are presented in Figure 1.

Table 1. Fuel properties [3,19,21,24].

Properties	Acetone	N-Butanol	Ethanol	Cottonseed Biodiesel (Bd)	Diesel (D)
Chemical formula	C ₃ H ₆ O	C ₄ H ₉ OH	C ₂ H ₅ OH	-	C ₁₂ -C ₂₅
Composition (C, H, O) (mass%)	62,10.5, 27.5	65,13.5, 21.5	-	9.2, 17.1, 2.9	-
Oxygen content, (mass%)	27.6	21.6	34.78	≈10	0.0
Density (kg/L)	0.971	0.810	0.795	0.864	0.82–0.86
Viscosity (mm ² /s) at 40 (°C)	0.35	2.22	1.08	3.7–4.14	1.9–4.1
Calorific values (MJ/kg)	29.6	33.1	26.8	37.5	42.8
Cetane number	-	17–25	8	52	48
Flash point (°C)	17.8	35	8	128	74
Boiling point (°C)	56.1	118	78.5	280–410	210–235
Latent heat vaporization (kJ/kg)	501.1	582	904	230	270
Auto-ignition temperature (°C)	560	385	434	-	≈300
Surface tension (mN/m)	22.6	24.2	22.27	32.4	23.8
Stoichiometric air–fuel ratio	9.54	11.2	9.02	12.5	15

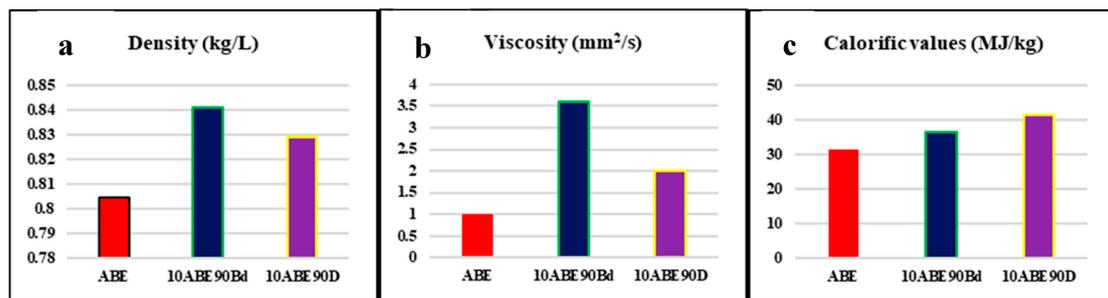


Figure 1. Measured fuel properties. (a) Density of test blends; (b) Viscosity of test blends; (c) Calorific values of test blends.

2.2. Spray Test Setup

The spray test was conducted at atmospheric condition. The setup was consistent with those described in previous work [4,16,20]. Figure 2 shows a schematic diagram of the spray setup system. The spray images were captured using a Photron SA3 high-speed camera. The injector driver specifications, injection setup and camera specification are presented Table 2. Image processing methods were the same as those employed in [4,16,20,26] using the MATLAB (2015R, The MathWorks, Natick, MA, USA) program.

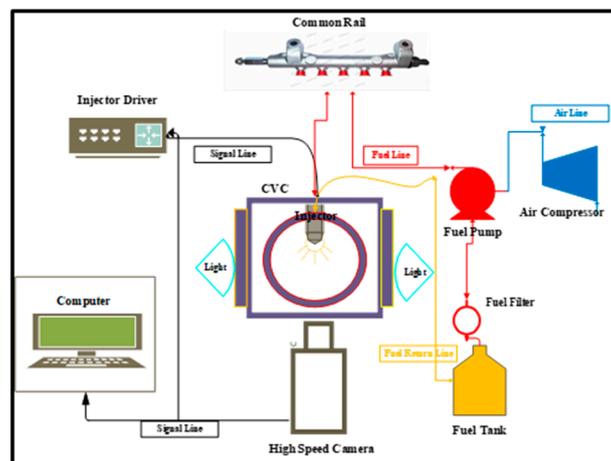


Figure 2. Schematic of spray setup system.

Table 2. Specification of visualization system [4,20].

Injector specification	
Injection type	Bosch electromagnetic common rail injectors solenoid type
Number of nozzles	6 holes
Nozzle diameter (nominal/measured)	0.18 mm.
Camera specification	
Camera resolution @ frame rate	1024 × 1024 pixels @ 2000 fps
A Nikon AF Micro-Nikkor lens with a focal length of 60 mm and a maximum aperture of f/2.8D with filter size 62 mm was connected to the camera	

Table 2. Cont.

Injection setup	
Injection Pressure (bar)	300
After start of injection time (ASOI) (mm)	0.5–1.5
Injection enclosed angle (degree)	156
Injection quantity (mg)	12
Repeat time	3

2.3. Engine Test Setup

The engine test consisted of a single-cylinder diesel engine, and a Coda gas analyzer used to measure emissions (Figure 3). Table 3 contains the engine specifications. The engine equipment and the Coda gas analyzer's accuracy ranges were used as described in previous work [16,25]. Specific fuel consumption (SFC) for each fuel test was measured using a flow rate meter because of the differences in density and heating values. Therefore, for each engine run, the test blend properties were included to measure the amount of fuel injected. Brake thermal efficiency (BTE) was calculated from the measured data.

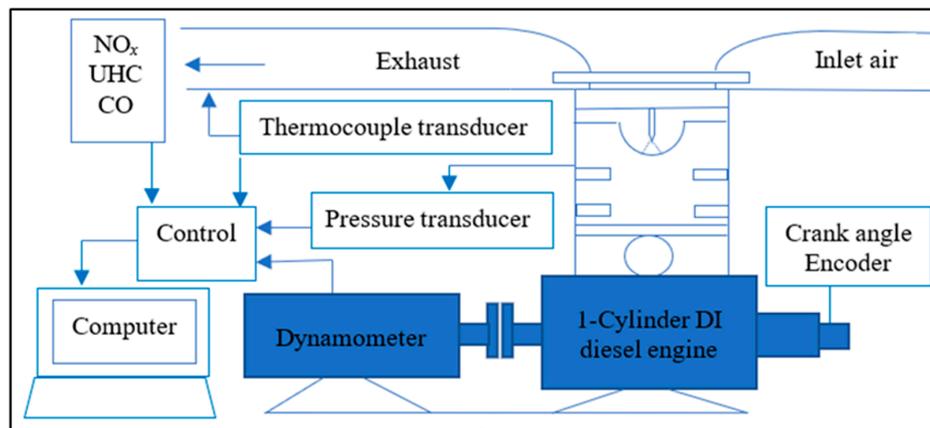


Figure 3. Schematic diagram of test set-up.

Table 3. Engine specifications [5,6].

Engine specifications	
Number of cylinders	1
Compression ratio	5:1–19:1
Bore (mm)	90
Stroke (mm)	74
Capacity (cm ³)	470
Connecting rod	128
Nozzle injection pressure (bar)	300
Nozzle diameter (mm)	0.18
Pressure sensor	Kistler 6052C transducer
Temperature sensor	Thermocouple transducer
Engine test condition	
Engine speeds test @ full load	1400, 2000 and 2600 RPM
Compression ratio test	19:1

3. Results and Discussion

3.1. Spray Characteristics

Spray images of the test fuels are displayed in Figure 4. These images are a sample of three images recorded in the test. The results are presented in Figures 5 and 6. Spray tip penetration (S) and spray cone angle (θ) were averaged from three images and six plumes.

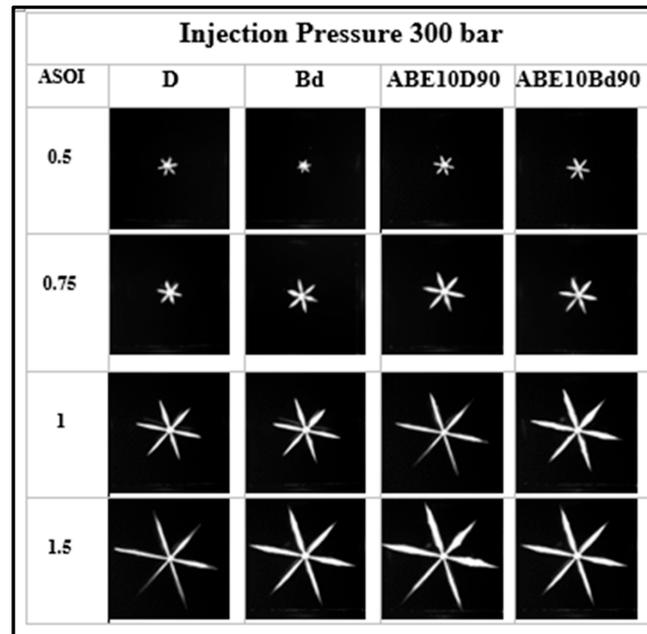


Figure 4. Spray comparison images of test blends.

Spray tip penetration of test fuel blends under different injection conditions is presented in Figure 5. Spray penetration was improved for all ABE test blends because of the low surface tension and viscosity of the ABE blends. The spray penetration of ABE-Bd and ABE-D blends increased, respectively, by 3–5% and 4–5% compared to neat biodiesel and diesel. The low viscosity and boiling point of alcohol can result in improved atomization and evaporation behavior of diesel and biodiesel [26,27]. Therefore, the reaction rate increased. Compared to other test fuels, the spray penetration of biodiesel was clearly shown to be lower due to its high viscosity [26]. Engine power reduction and fuel consumption increments may have occurred because of lower penetration and poorer atomization.

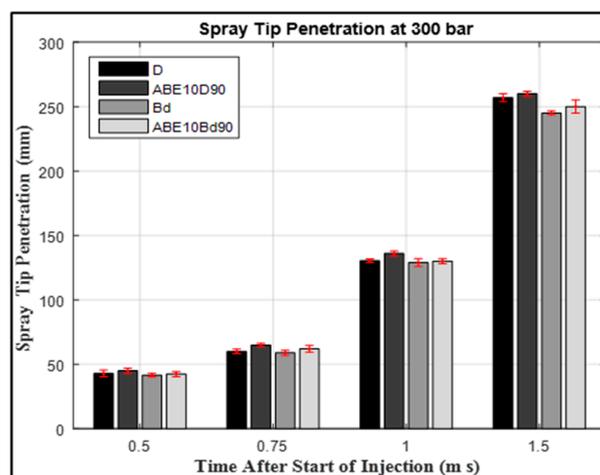


Figure 5. Spray tip penetration of test blends.

The spray cone angle of test blends is presented in Figure 6 under different times after start of injection (ASOI). The increase in injection pressure leads to a slight widening of the spray cone angle. However, the biodiesel fuel presented the maximum spray cone angle due to its high viscosity. In general, at 300 bar injection pressure, the spray cone angle of ABE-D/Bd blends increased at ASOI up to 0.75 ms, while the spray cone angle of neat biodiesel was higher at ASOI 0.5 ms. This result is consistent with the findings of previous work [16,26,27].

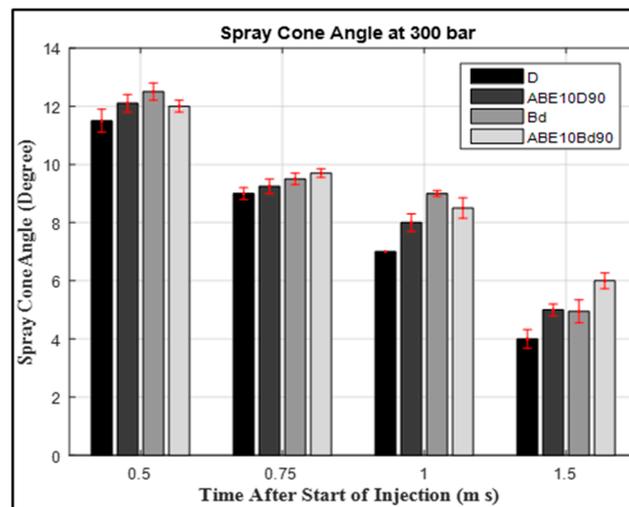


Figure 6. Spray cone angle of test blends.

3.2. Engine Performance

3.2.1. Maximum in-Cylinder Pressure

Figure 7 presents the relationship between the maximum in-cylinder pressure trace of the test fuels. The ABE10D90 blend gave a maximum peak of in-cylinder pressure at 5 bars higher than neat diesel due to the high oxygen content and low cetane number (CN) of the ABE blend. This resulted in increased ignition time and rapid in-cylinder pressure. However, an increase in the engine speed resulted in reduced in-cylinder pressure by about 10 bars. In-cylinder pressure was improved with the addition of ABE to the biodiesel blend. Spray and combustion characteristics enhanced the ABE-biodiesel blend due to a reduction in biodiesel viscosity.

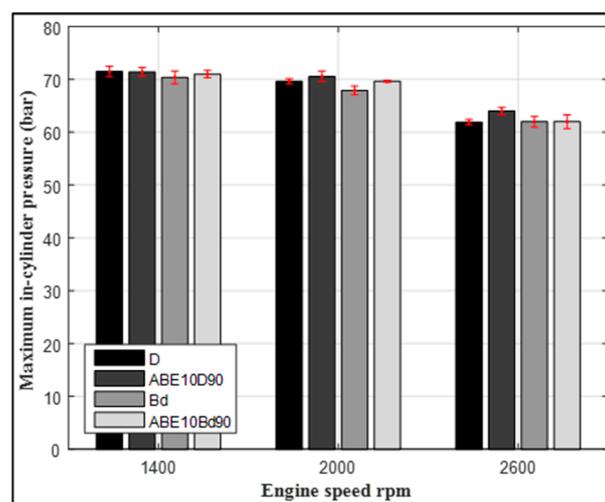


Figure 7. Maximum in-cylinder pressure test fuels.

3.2.2. BP and BTE

The engine was connected to an electrical dynamometer, which was used to measure engine brake power output (BP) at various engine speeds. Brake thermal efficiency (BTE) is the ratio between the brake powers of the engine and the fuel energy supplied to the engine.

Figure 8 shows the variation of BP with engine speed according to test fuel. Both the neat biodiesel (Bd) and ABE-Bd blend revealed a lower value of BP due to low heating values (Table 1 and Figure 1). ABE-D/Bd blends had a higher combustion efficiency because of their high oxygen content, which improved the combustion rate when used as an additive blend. Algayyim et al. [6] investigated the effect of BA-diesel blends in a diesel engine. The experimental results showed that BTE increased because of the addition of BA to the diesel blend. These increments in BTE were achieved because of increased oxygen content in the blend (Figure 9). Oxygen helped to improve combustion efficiency, particularly during the diffusion combustion phase. Another factor influencing the BTE was the cetane number. ABE-diesel/biodiesel fuel blends have a lower cetane number than diesel and biodiesel, causing longer ignition delay, and a wider range in the fraction of fuel burned in the premixed mode, which elevates BTE [23–25].

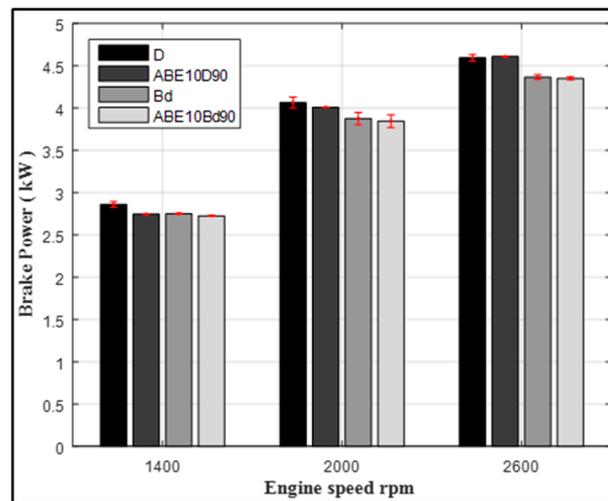


Figure 8. Brake power (BP) of test fuels.

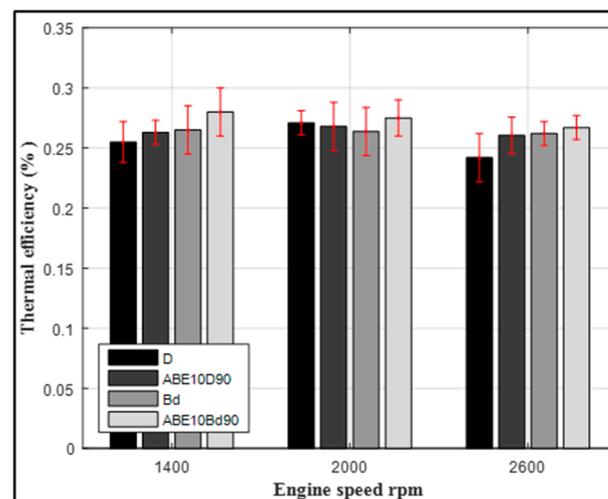


Figure 9. Thermal efficiency of test fuels.

3.2.3. EGT and NO_x Formation

Figures 10 and 11 show the relationship between the EGT and NO_x emissions of the test fuels at various engine speeds. The ABE-Bd blend showed a significant reduction in EGT compared to neat biodiesel at all engine speeds. Neat biodiesel showed higher NO_x emissions compared to conventional diesel (Figure 11) due to the high combustion temperature associated with biodiesel reaction [28–30]. Adding a blend such as acetone, butanol and ethanol creates lower boiling points, which result in an increased evaporation rate and combustion efficiency. Therefore, EGT will be reduced. EGT and NO_x emissions were reduced with the ABE blend to neat diesel and biodiesel by 14–17% and 11–13%, respectively. This result agrees with other work [30–35].

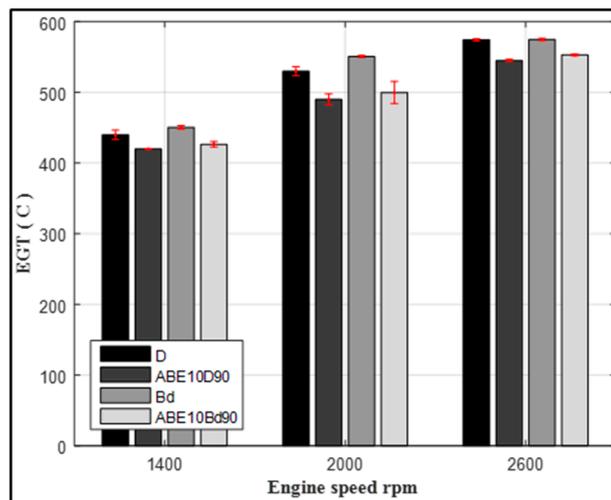


Figure 10. Exhaust gas temperature (EGT) of test fuels.

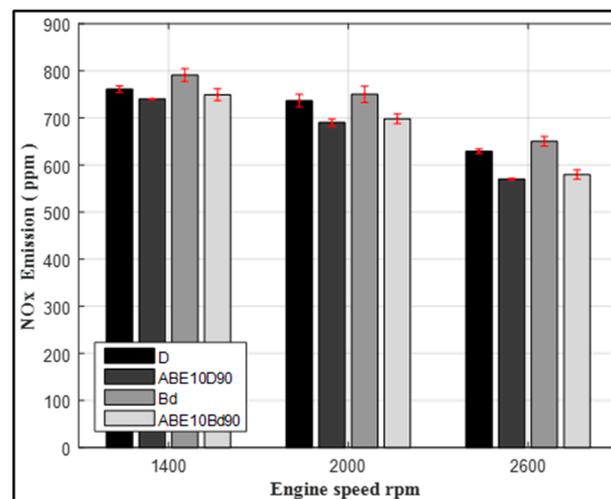


Figure 11. NO_x emissions of test fuels.

3.2.4. UHC, CO and CO₂ Emissions

The use of the ABE-D blend decreased UHC emissions compared to neat diesel at medium and high engine speeds (Figure 12). This reduction occurred because the boiling point of the ABE blend was low, which improved the vaporization rate and promoted combustion performance. The difference in droplet lifetime between ABE (3.25 s/mm²) and diesel (3.75 s/mm²) affected the reaction time of ABE blends at 823 K, which resulted in increased mixing time and led to complete reaction resulting in decreased UHC emissions [7]. ABE-biodiesel blends increased the UHC emissions due to the high

oxygen atom (biodiesel and ABE), which altered the electronic structure. Almost all the C-H bonds of the ABE-Bd blend are less active for reaction compared to hydrocarbon fuels (fossil fuels), which means more time is required to complete the reaction and increases UHC emissions [36,37]. UHC emissions were reduced by 13% when ABE was added to diesel. However, UHC emissions were increased by 25–34% when ABE was added to biodiesel blends. All neat biodiesel and ABE-biodiesel/diesel blends presented lower CO emissions at all engine speeds due to the high oxygen content (Figure 13). This result agrees with previous work [34–37]. Moreover, the oxygen content of ABE-Bd blend was higher than biodiesel resulting in a significant reduction in CO emissions compared to neat biodiesel and ABE-diesel blends. CO₂ emissions were slightly increased of ABE10Bd90 blends (Figure 14). It is clear that ABE0-D and ABE-Bd blends produced less CO emissions compared to diesel due to the lower carbon-to-hydrogen ratio [31,33,37].

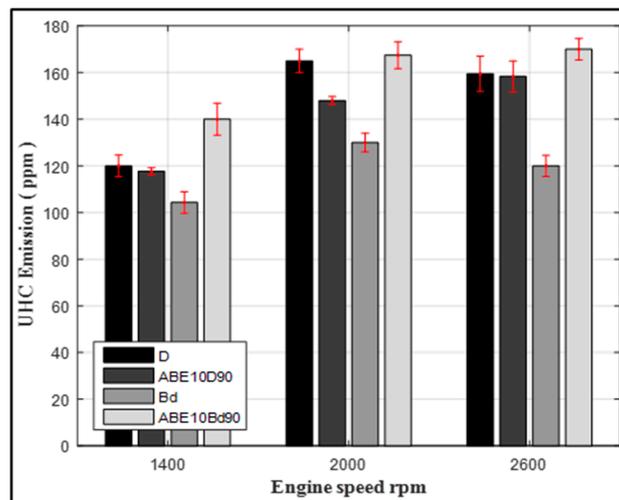


Figure 12. Unburnt hydrocarbon (UHC) emissions of test fuels.

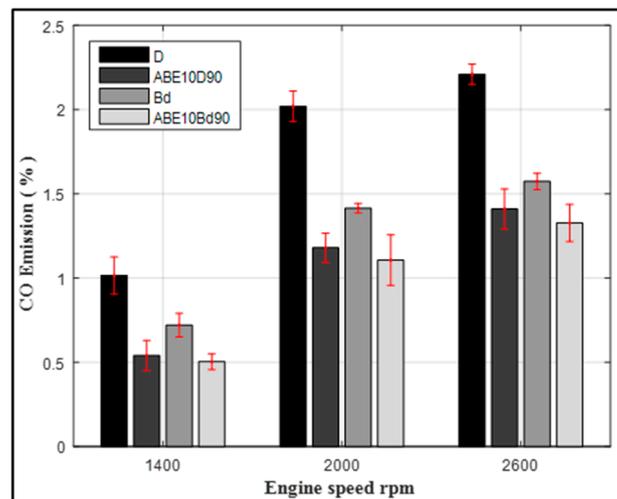


Figure 13. CO emissions of test fuels.

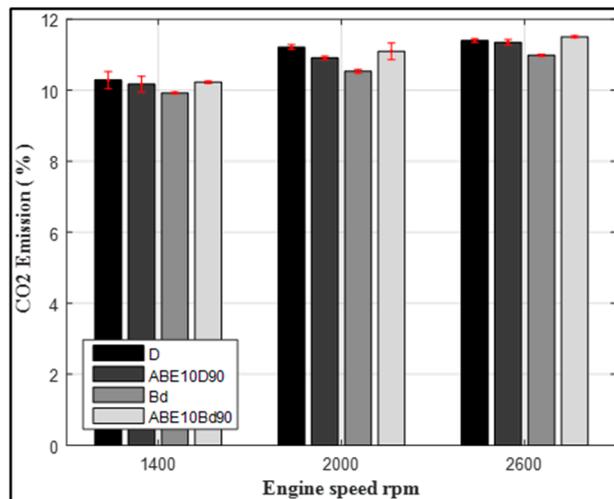


Figure 14. CO₂ emissions of test fuels.

4. Conclusions

ABE mixture can increase the spray penetration of neat diesel and biodiesel resulting in improved atomization. The ABE10D90 blend gives a maximum in-cylinder pressure value 5 bars higher than neat diesel. The Bd and ABE-Bd blends gave a lower value of BP due to the low heating values. EGT, NO_x and CO emissions were significantly reduced with the addition of the ABE blend to both neat diesel and biodiesel. UHC emissions were reduced when ABE was added to diesel. However, UHC emissions were increased when ABE was added to biodiesel. Thus, it can be concluded that the ABE mixture could be a good additive blend for neat diesel rather than neat biodiesel for improving diesel properties by using green energy for CI engines with no or minor modifications.

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