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Effectiveness of Ethyl Acetate, 1-Octanol, and Soy Biodiesel in Stabilizing Ethanol−Diesel Fuel Blends and Performance of Compression Ignition Engine on Stabilized Fuel Blends

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ABSTRACT: A study was conducted to evaluate ethyl acetate, soy biodiesel, and 1-octanol as surfactants for stabilization of ethanol−diesel fuel blends. The evaluation was based on the temperature stability and engine performance of ethanol−diesel fuel blends stabilized by selected surfactants. Among the three selected surfactants, 1-octanol was most effective in stabilizing ethanol−diesel fuel blends. Out of 20 ethanol−diesel fuel blends prepared with 1-octanol as surfactant, only 3 blends showed distinct phase separation; the rest 17 remained stable in the entire temperature range of 0−45 °C. At the rated engine speed, eight ethanol−diesel fuel blends showed similar power-producing capability as that of diesel. The engine running on diesel developed a power of 3.71 kW, while the engine brake power with ethanol−diesel fuel blends was in the range of 3.67−3.74 kW at the rated load condition. The tested fuel blends resulted in slightly higher fuel consumption and increased emission of unburnt hydrocarbons as compared to the diesel fuel. The tested fuel blends had comparable thermal efficiency and acceptable UBHC and NO_x emissions compared to diesel.
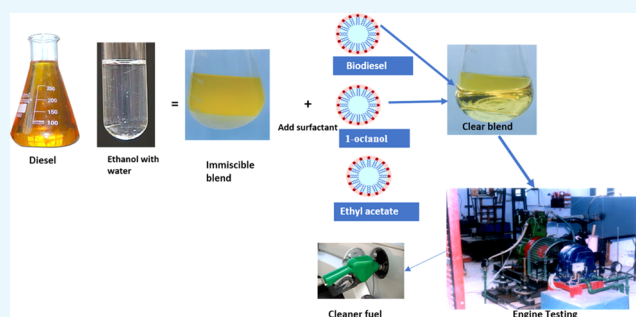
1. INTRODUCTION

Energy is the primary need for the economic development of any country. India is the third largest energy consumer in the world after US and China, and consumed about 806.1 million tons of oil equivalent (Mtoe) in 2019. During 2019−20, the consumption of petroleum products in India was 214.13 million metric tons (MMT), in which diesel accounted for the highest consumption share (38.9%), followed by petrol (14%). The domestic production of crude oil during the year 2019−20 was at 32.17 MMT; thus, India imports nearly 85 percent of its crude oil to meet the domestic need.[1] India spent USD 61.9 billion in 2020−21 on import of 198.2 million tons of crude oil. Higher dependence on crude oil import and frequent fluctuations in petroleum prices have made the Indian economy insecure. The inflation trends are hurting the common man badly.[2] In order to reduce the consumption of petroleum-based fuels and to protect the environment, use of alternative fuels has become necessary. Diesel engines serve as an essential component of industries, with transportation, agriculture, and electricity production being the major users of diesel engines.[3] However, these engines tend to be more costly, emit harmful HC, CO, and NO_x emissions, and are major contributors to air pollution.[4] Sustainable renewable sources like alcohol and biodiesel have received major focus in recent times as a potential substitute to conventional diesel fuels.[5,6] Blending of alcohols like methanol

and ethanol with diesel fuel has the potential to improve fuel properties and reduce emission of greenhouse gases.[7,8] Alcohols, because of the presence of the oxygen molecule, have a complete combustion potential, enhancing the combustion efficiency and reducing particulate matter, carbon residue formation, and engine knock.[9−11] Furthermore, addition of alcohol to diesel fuel improves blend properties like viscosity, lubricity, cetane number, and overall ignitability.[12−14] For this reason, the blending of alcohol in certain proportions with diesel fuel to run diesel engines is suggested.[15] Biodiesel−ethanol blends are more effective than biodiesel−methanol, and more economical and environmentally friendly than biodiesel and petroleum-based fuels.[16−18] However, the use of ethanol with diesel has several limitations. The most important disadvantage is its limited miscibility in diesel fuel caused by molecular structure, dependence on temperature, degree proof of ethanol, and overall percentage of ethanol in the fuel blend.[19,20] Miscibility varies with both the proportion of the ethanol−diesel fuel blend
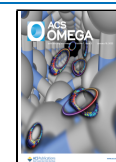
Table 1. Ethanol−Diesel Microemulsions Prepared with Different Proofs of Ethanol Using Ethyl Acetate as Surfactant

fuel blend	microemulsion type [0] proof ethanol (diesel−ethanol−ethyl acetate)	proportion of fuel constituents in microemulsions			percent of fuel constituents in microemulsion			diesel replacement (%)
		diesel	ethanol	ethyl acetate	diesel	ethanol	ethyl acetate	
DEE1	200[0][1:0.053:0.01]	1	0.053	0.01	94.06	4.95	0.99	5.94
DEE2	200[0] [1:0.11:0.06]	1	0.11	0.06	84.91	9.43	5.66	15.09
DEE3	200[0] [1:0.18:0.15]	1	0.18	0.15	74.89	13.22	11.89	25.11
DEE4	200[0] [1:0.25:0.21]	1	0.25	0.21	68.09	17.02	14.89	31.91
DEE5	195[0][1:0.053:0.10]	1	0.053	0.1	86.36	4.55	9.09	13.64
DEE6	195[0] [1:0.11:0.20]	1	0.11	0.2	76.27	8.47	15.25	23.73
DEE7	195[0][1:0.18:0.24]	1	0.18	0.24	70.45	12.43	17.12	29.55
DEE8	195[0] [1:0.25:0.29]	1	0.25	0.29	64.78	16.19	19.03	35.22
DEE9	190[0][1:0.053:0.18]	1	0.053	0.18	80.51	4.24	15.25	19.49
DEE10	190[0][1:0.11:0.26]	1	0.11	0.26	72.87	8.10	19.03	27.13
DEE11	190[0][1:0.18:0.40]	1	0.18	0.40	63.20	11.15	25.65	36.80
DEE12	190[0] [1:0.25:0.45]	1	0.25	0.45	58.82	14.71	26.47	41.18
DEE13	185[0][1:0.053:0.27]	1	0.053	0.27	75.10	3.95	20.95	24.90
DEE14	185[0] [1:0.11:0.33]	1	0.11	0.33	69.23	7.69	23.08	30.77
DEE15	185[0][1:0.18:0.45]	1	0.18	0.45	61.37	10.83	27.80	38.63
DEE16	185[0] [1:0.25:0.50]	1	0.25	0.50	56.94	14.23	28.83	43.06
DEE17	180[0][1:0.053:0.31]	1	0.053	0.31	73.08	3.85	23.08	26.92
DEE18	180[0] [1:0.11:0.43]	1	0.11	0.43	64.52	7.17	28.32	35.48
DEE19	180[0] [1:0.18:0.50]	1	0.18	0.50	59.44	10.49	30.07	40.56
DEE20	180[0] [1:0.25:0.61]	1	0.25	0.61	53.69	13.42	32.89	46.31

Table 2. Ethanol−Diesel Microemulsions Prepared with Different Proofs of Ethanol Using 1-Octanol as Surfactant

fuel blend	microemulsion type [0] proof ethanol (diesel−ethanol− 1-octanol)	proportion of fuel constituents in microemulsions			percent of fuel constituents in microemulsion			diesel replacement (%)
		diesel	ethanol	1-octanol	diesel	ethano	1-octanol	
DEO1	200[0][1:0.053:0.052]	1	0.053	0.052	94.53	4.98	0.50	5.47
DEO2	200[0] [1:0.11:0.06]	1	0.11	0.06	85.31	9.48	5.21	14.69
DEO3	200[0] [1:0.18:0.07]	1	0.18	0.07	80.19	14.15	5.66	19.81
DEO4	200[0] [1:0.25:0.09]	1	0.25	0.09	74.42	18.60	6.98	25.58
DEO5	195[0][1:0.053:0.03]	1	0.053	0.03	91.79	4.83	3.38	8.21
DEO6	195[0] [1:0.11:0.07]	1	0.11	0.07	84.91	9.43	5.66	15.09
DEO7	195[0][1:0.18:0.08]	1	0.18	0.08	79.44	14.02	6.54	20.56
DEO8	195[0] [1:0.25:0.1]	1	0.25	0.1	74.07	18.52	7.41	25.93
DEO9	190[0][1:0.053:0.06]	1	0.053	0.06	89.62	4.72	5.66	10.38
DEO10	190[0] [1:0.11:0.09]	1	0.11	0.09	82.95	9.22	7.83	17.05
DEO11	190[0][1:0.18:0.13]	1	0.18	0.1	76.58	13.51	9.91	23.42
DEO12	190[0] [1:0.25:0.15]	1	0.25	0.15	71.43	17.86	10.71	28.57
DEO13	185[0][1:0.053:0.09]	1	0.053	0.09	87.16	4.59	8.26	12.84
DEO14	185[0] [1:0.11:0.11]	1	0.11	0.11	81.45	9.05	9.50	18.55
DEO15	185[0][1:0.18:0.14]	1	0.18	0.14	75.56	13.33	11.11	24.44
DEO16	185[0] [1:0.25:0.20]	1	0.25	0.20	68.97	17.24	13.79	31.03
DEO17	180[0][1:0.053:0.13]	1	0.053	0.13	84.44	4.44	11.11	15.56
DEO18	180[0] [1:0.11:0.15]	1	0.11	0.15	79.30	8.81	11.89	20.70
DEO19	180[0] [1:0.18:0.19]	1	0.18	0.19	72.96	12.88	14.16	27.04
DEO20	180[0] [1:0.25:0.23]	1	0.25	0.23	67.23	16.81	15.97	32.77

and the temperature. For example, blending of ethanol with diesel fuel below 10 °C in certain proportions results in development of two immiscible phases.[21,22] To solve this issue, different techniques have been explored and applied, including fumigation of ethanol into intake air charge, mixing ethanol with diesel fuel just before injection, using a cosolvent or emulsifier, or using a separate injection system for each fuel.[23−26] By use of a suitable emulsifier, the amount of diesel substitution in the alcohol−diesel fuel blend can be enhanced to a large extent.[27,28] As all automotive fuels need to be clear and single-phase liquids, a number of commercially available surfactants are used as emulsifiers to form ethanol−diesel fuel blends. However,

information on the performance of such surfactants in improving the stability of the ethanol−diesel blend and engine emission characteristics, especially with different proof of ethanol, is limited, and hence these need to be studied.[29] To address this issue, three surfactants (1-octanol, soy biodiesel, and ethyl acetate) were evaluated for their use in the formation of stable ethanol−diesel fuel blends. The stable ethanol−diesel blends were evaluated for their performance in the existing compression engines.

Table 3. Ethanol−Diesel Microemulsions Prepared with Different Proofs of Ethanol Using Soy Biodiesel as Surfactant

| fuel blend	microemulsion type ^{0} proof ethanol (diesel−ethanol−biodiesel)	proportion of fuel constituents in microemulsions			percent of fuel constituents in microemulsion			diesel replacement (%)
		diesel	ethanol	biodiesel	diesel	ethanol	biodiesel	
DEB1	200^0[1:0.053:0.14]	1	0.053	0.14	83.33	4.39	12.28	16.66
DEB2	200^0 [1:0.11:0.20]	1	0.11	0.20	76.27	8.47	15.25	23.73
DEB3	200^0 [1:0.18:0.24]	1	0.18	0.24	70.25	12.40	17.36	29.75
DEB4	200^0 [1:0.25:0.30]	1	0.25	0.30	64.52	16.13	19.35	35.48
DEB5	195^0[1:0.053:0.33]	1	0.053	0.33	71.97	3.79	24.24	28.03
DEB6	195^0 [1:0.11:0.54]	1	0.11	0.55	60.40	6.71	32.89	39.60
DEB7	195^0 [1:0.18:0.71]	1	0.18	0.70	52.96	9.35	37.69	47.04
DEB8	195^0 [1:0.25:0.80]	1	0.25	0.80	48.63	12.16	39.21	51.37
DEB9	190^0[1:0.053:0.36]	1	0.053	0.36	70.37	3.70	25.93	29.63
DEB10	190^0 [1:0.11:0.62]	1	0.11	0.62	57.69	6.41	35.90	42.31
DEB11	190^0[1:0.18:0.77]	1	0.18	0.77	51.20	9.04	39.76	48.79
DEB12	190^0 [1:0.25:0.90]	1	0.25	0.90	46.51	11.63	41.86	53.48
DEB13	185^0[1:0.053:0.40]	1	0.053	0.40	68.59	3.61	27.80	31.41
DEB14	185^0 [1:0.11:0.63]	1	0.11	0.63	57.32	6.37	36.31	42.68
DEB15	185^0[1:0.18:0.83]	1	0.18	0.83	49.71	8.77	41.52	50.29
DEB16	185^0 [1:0.25:1.14]	1	0.25	1.14	41.80	10.45	47.75	55.80
DEB17	180^0[1:0.053:0.44]	1	0.053	0.44	66.67	3.51	29.82	33.33
DEB18	180^0 [1:0.11:0.77]	1	0.11	0.77	52.94	5.88	41.18	47.06
DEB19	180^0[1:0.18:1.07]	1	0.18	1.07	44.39	7.83	47.78	55.61
DEB20	180^0 [1:0.25:1.54]	1	0.25	1.54	35.79	8.95	55.26	64.21
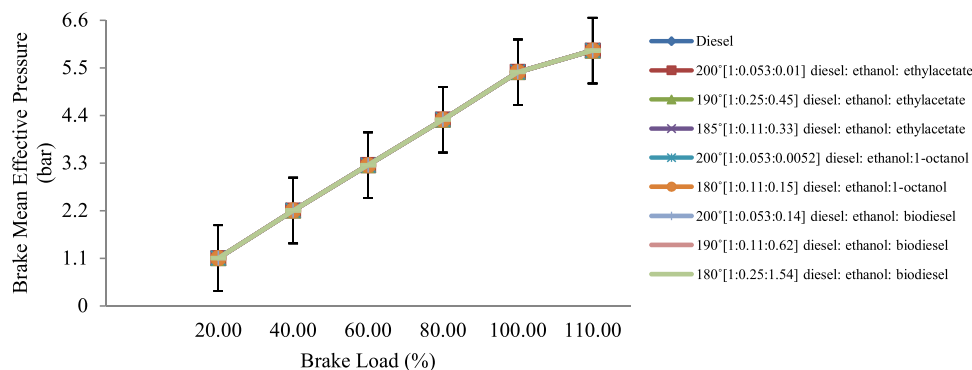
Figure 1. Variation of BMEP with varying engine brake load conditions.

2. MATERIALS AND METHODS

The major limitation of blending ethanol with diesel is its immiscibility over a wide temperature range. As a result, replacement of diesel with ethanol in ethanol−diesel fuel blend is limited by the occurrence of a distinct phase separation. Experiments were conducted on preparation of stable fuel blends with different ethanol proofs and high-speed diesel (HSD) using soy biodiesel, 1-octanol, and ethyl acetate as surfactants. The experiment was conducted using anhydrous ethanol and ethanol proofs of 170,175, 180, 185, 190, and 195° prepared from the anhydrous ethanol, with distilled water added in the required amount. The degree proof of ethanol represented double the percentage of ethanol (volume basis) in the blend. Thus, 200° proof represented 100% ethanol, i.e., pure-(anhydrous) ethanol. The 195° proof ethanol was prepared by using 2.5% distilled water (v/v), while 170° proof ethanol was prepared by using 15% distilled water (v/v).

2.1. Preparation of Ethanol−Diesel Blends with Different Surfactants. The ethanol−diesel fuel blends with different proofs of ethanol were prepared at a room temperature of 25 °C by simple splash blending using ethyl acetate, 1-octanol, and soy biodiesel as surfactants. The quality of different blends

was analyzed in terms of stability, homogeneity, surfactant required, and amount of diesel replacement. Initially, 20 mL samples were prepared for each proof of ethanol by varying the percentage of ethanol proof in diesel from 5 to 20% in intervals of 5%. For 5% ethanol−diesel blend, 1 mL of ethanol was added to 19 mL of diesel, and for 20% ethanol blend, 4 mL of ethanol was added to 16 mL of ethanol. The surfactant was added to each of these 20 mL samples in such a way that minimum surfactant was required to get a clear and transparent blend without any visible sign of phase separation. The proof of ethanol used varied from 200 to 180° in the interval of 5°. Thus, 60 blends of ethanol−diesel were prepared, twenty each with three selected surfactants (Tables 1−3).

2.2. Study of Temperature Stability of Ethanol−Diesel Fuel Blends. The sixty fuel blends prepared were found stable at ambient temperature after twenty-four hours (24 h) from the time of blend preparation. These fuel blends were further tested at temperatures of 0, 5, 10, 15, 20, 25, 30, 35, 40, and 45 °C to observe their stability under a wide temperature range. The stability test was conducted by exposing the fuel blend samples for 8 h at a selected temperature in a temperature control chamber designed to operate in the 0−50 °C temperature range.

Initially the temperature control chamber was set at 45 °C and the samples were kept for 8 h at that temperature to observe the fuel blend stability by visual inspection. After this, the temperature of control chamber was maintained at 40, 35, 30, 25, 20, 15, 10, 5, and 0 °C and the samples were placed at each of these temperatures for 8 h to observe phase separation, if any. The fuel blends that were found stable throughout the temperature range of 0−45 °C were selected for further experimental study.

2.3. Study of Engine Performance with Selected Fuel Blends. Based on temperature stability, diesel replacement, and fuel properties, eight fuel blends were selected for the study of engine performance. The selected fuel blends were DEE1, DEE12, DEE14, DEO1, DEO18, DEB1, DEB10, and DEB20, and diesel fuel was also selected as a base fuel to make the comparison. The engine selected for the study was a 3.73 kW four-stroke, constant-speed, single-cylinder, direct-injection CI engine (Make: Kirloskar; Model: AV1). This engine is in common use for agricultural operations and in electric generators as a prime mover, and has a rated speed of 1500 rpm. The engine was loaded using a test setup containing an electronic controlled eddy current dynamometer (make: SAJ-Froude, model: EC-15). The engine was evaluated for its performance on the selected fuel blends and diesel by measuring parameters like brake mean effective pressure (Pa), brake power (kW), fuel consumption (L/h), brake specific fuel consumption (kg/kWh), brake thermal efficiency (%), energy input (MJ/h), unburnt hydrocarbon emission (%), nitric oxide (ppm), and nitrogen dioxide (ppm). The engine performance test involved fuel consumption and emission tests.

2.3.1. Fuel Consumption Test. The fuel consumption test on the selected fuel blends and diesel fuel was conducted as per the Bureau of Indian Standards.[30] The fuel consumption test was done at no load, 20, 40, 60, 80, 100, and 110% of the rated load conditions. The engine was run at each of the load conditions at least for 3 min, and thereafter, different performance parameters were measured at the selected load conditions as follows.

2.3.1.1. Engine Speed. The engine speed, v_{engine} (in rpm), at different loading conditions of the engine was recorded directly from the electronic controller unit of the eddy current dynamometer.

2.3.1.2. Engine Brake Power (BP). The brake power developed by the engine with the selected fuel blends, P_{brake} (in kW), was determined as follows:

$$P_{brake} = \frac{v_{engine} \cdot \tau_{engine}}{d}$$

where τ_{engine} is the engine torque (in N·m) and d is the dynamometer constant (9549.305).

2.3.1.3. Brake-Specific Fuel Consumption. The brake-specific fuel consumption (bsfc) of the engine was measured using an electronic volumetric fuel consumption measurement unit (make: SAJ-Froude, model: SFV-75). The fuel measurement unit consisted of a fuel tank, graduated glass pipette (25, 50, 75 mL), solenoid valve, timer, and a photosensor assembly. The fuel supply to the engine was made to pass through the glass pipette of 25 mL size. The time taken by the engine for 25 mL fuel consumption was recorded by means of an inbuilt timer. The bsfc (in kg·kW^{-1}·h^{-1}) was determined using the following relationship:

$$bsfc = \frac{V_{fc} \cdot \rho_{fuel} \cdot 3.6}{P_{brake} \cdot t_{fc}}$$

where V_{fc} is the fuel consumption volume (in cm^3), ρ_{fuel} is the fuel density (in g·cm^{-3}), and t_{fc} is the time taken by the engine for 25 mL fuel consumption (in s).

2.3.1.4. Brake Thermal Efficiency. The brake thermal efficiency, η_t (in %), at different load conditions of the engine was determined using the following equation:

$$\eta_t = \frac{3600}{H_{comb} \cdot bsfc} \times 100\%$$

where H_{comb} is the gross heat of combustion (in kJ·kg^{-1}).

2.3.1.5. Brake Mean Effective Pressure. The brake mean effective pressure of the engine, BMEP (in Pa), was calculated at different conditions using the following relationship:

$$BMEP = \frac{2 \cdot P_{brake} \cdot 60 \times 10^{12}}{L_{stroke} \cdot A_{piston} \cdot v_{engine} \cdot N_{cyl}}$$

where L_{stroke} is the stroke length (in mm), A_{piston} is the cross-sectional area of the piston (in mm^2), and N_{cyl} is the number of cylinders.

2.3.1.6. Energy Input. The energy input of the engine, E_{input} (in MJ·h^{-1}), at varying brake load conditions and with different fuel blends was calculated as follows:

$$E_{input} = H_{fuel} \cdot \rho_{fuel} \cdot R_{fc}$$

where H_{fuel} (in MJ·kg^{-1}) is the calorific value of the fuel and R_{fc} is the rate of fuel consumption (in L·h^{-1}).

2.3.2. Measurement of Exhaust Emissions. The emission characteristics of the engine on the selected fuel types were studied in terms of unburnt hydrocarbons, nitrogen dioxide, and nitric oxide.

2.3.2.1. Unburnt Hydrocarbons. The unburnt hydrocarbon (UBHC) in the exhaust gases at different load conditions was measured using a gas analyzer (make: Nucon, model: 4900; range: 0−10%). An air pump operating at 230 V (AC) was used to feed the exhaust gas sample into the analyzer. The air pump drew the air sample from the exhaust manifold through a PVC tube of 3 mm diameter and fed it to the gas analyzer. The electrochemical sensor present in the analyzer indicated the UBHC percent in the exhaust gas.

2.4.2.2. Nitric Oxide. The nitric oxide concentration in the engine exhaust gases was measured using a nitric oxide analyzer (make: Nucon, model: 500-NO; range: 0−19999 ppm). The analyzer was operated at 230 V (AC) and had an inbuilt electrochemical transducer. Similar to UBHC measurement, a sample of exhaust gas was drawn through an air pump from the exhaust manifold and fed to the analyzer.

2.4.2.3. Nitrogen Dioxide. The concentration of nitrogen dioxide in the engine exhaust gases emanating from the combustion of the tested fuel blends was measured using a nitrogen dioxide gas analyzer (Make: Nucon, model: 500-NO$_2$). The analyzer had a range of 0−1999 ppm, and sampling was done similar to the nitric oxide measurement.

3. RESULTS AND DISCUSSION

3.1. Effectiveness of Ethyl Acetate, 1-Octanol, and Soy Biodiesel in Stabilizing Ethanol−Diesel Fuel Blends. The comparative analysis of surfactants in stabilizing ethanol−diesel fuel blends was carried out based on the surfactant required to stabilize a particular blend and the temperature stability of the fuel blend. The quantity of surfactant required to stabilize a particular ethanol−diesel blend and the temperature stability of

Table 4. Engine Speed and Brake Power Developed by the Test Engine at Different Brake Mean Effective Pressures on the Selected Ethanol−Diesel Fuel Blends

| | | | | diesel−ethanol−ethyl acetate fuel blends | | | | | | diesel−ethanol−1-octanol fuel blends | | | | | | diesel−ethanol−biodiesel fuel blends | | | |
| | | diesel | | 200⁰[1:0.053:0.01] | | 190⁰[1:0.25:0.45] | | 185⁰[1:0.11:0.33] | | 200⁰[1:0.053:0.0052] | | 180⁰[1:0.11:0.15] | | 200⁰[1:0.053:0.14] | | 190⁰[1:0.11:0.62] | | 180⁰[1:0.25:1.54] | |
brake load (%)	brake mean effective pressure (bar)	engine speed (rpm)	brake power (kW)	engine speed (rpm)	brake power (kW)	engine speed (rpm)	brake power (kW)	engine speed (rpm)	brake power (kW)	engine speed (rpm)	brake power (kW)	engine speed (rpm)	brake power (kW)	engine speed (rpm)	brake power (kW)	engine speed (rpm)	brake power (kW)	engine speed (rpm)	brake power (kW)
no load		1585	0.00	1580	0.00	1567	0.00	1566	0.00	1572	0.00	1579	0.00	1566	0.00	1530	0.00	1544	0.00
20	1.1	1555	0.78	1532	0.77	1528	0.77	1530	0.77	1534	0.77	1541	0.77	1530	0.77	1505	0.76	1522	0.77
40	2.2	1524	1.52	1510	1.50	1516	1.51	1527	1.52	1525	1.52	1534	1.53	1527	1.52	1496	1.49	1507	1.50
60	3.25	1514	2.27	1507	2.26	1504	2.25	1521	2.28	1517	2.27	1519	2.27	1521	2.28	1488	2.23	1495	2.24
80	4.3	1504	2.99	1502	2.99	1496	2.98	1519	3.02	1512	3.01	1514	3.01	1519	3.02	1481	2.95	1487	2.96
100	5.4	1493	3.71	1497	3.72	1486	3.69	1507	3.74	1501	3.73	1506	3.74	1507	3.74	1478	3.67	1480	3.67
110	5.9	1465	4.00	1468	4.01	1465	4.00	1477	4.04	1470	4.02	1481	4.05	1477	4.04	1460	3.99	1458	3.98

Table 5. Fuel Consumption of the Test Engine with Selected Ethanol−Diesel Fuel Blends at Different Brake Mean Effective Pressures

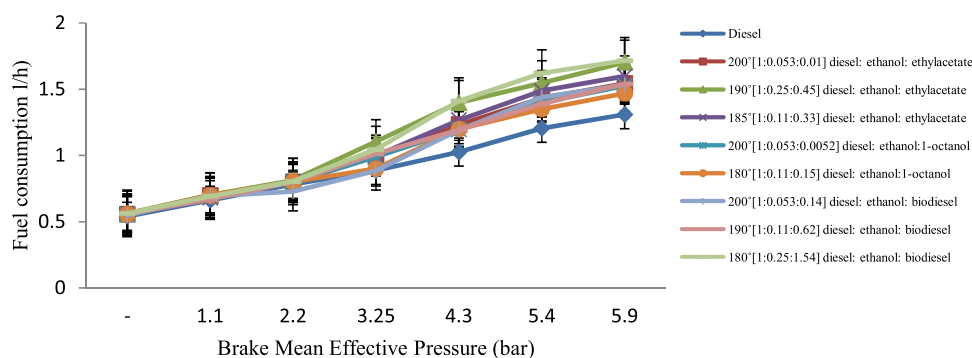| | | | diesel−ethanol−ethyl acetate fuel blends | | | diesel−ethanol−1-octanol fuel blends | | | diesel−ethanol−biodiesel fuel blends | |
brake load (%)	brake mean effective pressure (bar)	diesel	200⁰[1:0.053:0.01]	190⁰[1:0.25:0.45]	185⁰[1:0.11:0.33]	200⁰[1:0.053:0.0052]	180⁰[1:0.11:0.15]	200⁰[1:0.053:0.14]	190⁰[1:0.11:0.62]	180⁰[1:0.25:1.54]
						Fuel Consumption (L/h)				
no load		0.541	0.557	0.563	0.559	0.557	0.558	0.547	0.561	0.563
20	1.1	0.662	0.699	0.701	0.680	0.690	0.699	0.693	0.670	0.692
40	2.2	0.783	0.800	0.812	0.799	0.795	0.801	0.729	0.801	0.804
60	3.25	0.887	0.992	1.104	0.998	0.989	0.9	0.885	1.012	1.045
80	4.3	1.026	1.232	1.398	1.267	1.196	1.199	1.191	1.193	1.410
100	5.4	1.205	1.432	1.547	1.488	1.400	1.35	1.439	1.390	1.622
110	5.9	1.309	1.543	1.702	1.597	1.526	1.469	1.533	1.540	1.715

Figure 2. Fuel consumption of different blends at varying BMEP.

the resulting fuel blends revealed that 1-octanol was the most effective surfactant among the three selected surfactants. Out of 20 blends prepared with 1-octanol as surfactant, only 3 blends showed distinct phase separation; the rest 17 remained stable in the entire temperature range. It was found that only 0.1 mL of 1-octanol can stabilize a blend of 20 mL containing 95% diesel and 5% ethanol of 200° proof. In the case of ethyl acetate, out of 20 blends, 7 showed distinct phase separation. The amount of ethyl acetate required to stabilize a particular blend was higher than that of 1-octanol. The minimum amount (0.2 mL) of ethyl acetate requirement for a 20 mL fuel blend was found in the ethanol−diesel blend containing 5% ethanol (200° proof) and 95% diesel. The maximum amount of ethyl acetate (9.8 mL) was required in an ethanol−diesel blend containing 20% ethanol (180° proof) and 80% diesel in a total blend volume of 20 mL.

The biodiesel requirement as a surfactant to stabilize a particular ethanol−diesel blend was higher compared to 1-octanol and ethyl acetate. The minimum and maximum amounts of biodiesel required to stabilize an ethanol−diesel blend was 2.8 and 24.7 mL, respectively, for a blend volume of 20 mL. Biodiesel as surfactant was required minimum for a blend containing 5% ethanol of 200° proof and 95% diesel, whereas the maximum was for a blend of 20% ethanol of 180° proof and 80% diesel. Out of 20 fuel blends prepared with biodiesel as surfactant, only three showed distinct phase separation, while the remaining seventeen remained stable in the entire temperature range of 0−45 °C.

3.2. Performance of the Engine on Selected Ethanol−Diesel Fuel Blends Stabilized with Different Surfactants. From the engine testing, the following major results were observed:

3.2.1. Brake Mean Effective Pressure. The brake mean effective pressure (BMEP) of the engine at selected load conditions (no load, 20, 40, 60, 80, 10, and 110% of brake loads) on diesel and selected ethanol−diesel fuel blends showed a linear relation (Figure 1). From the figure, it is clear that with a very 20% increase in brake load, the BMEP increased by about 1.1 bar. With increase in brake power from 100 to 110%, the BMEP proportionately increased by 0.5 bar.

3.2.2. Brake Power. At full-load condition, the brake power developed by a diesel-fueled engine was 3.71 kW at an engine rpm of 1496. The rated brake power specified by the manufacturer for the selected engine was 3.73 kW at a speed of 1500 rpm. The data indicated an increase of brake power and a decrease of engine speed with the increase in brake mean effective pressure of the engine for all selected fuel blends. The engine developed a brake power of 3.72, 3.69, 3.74, 3.73, 3.74, 3.67, and 3.67 kW at the rated load condition for fuel blends

DEE1, DEE12, DEE14, DEO1, DEO18, DEB1, DEB10, and DEB20, respectively (Table 4). The fuel blends DEE12, DEB10, and DEB20 showed a lower brake power and engine speed at the rated load than diesel. This may be due to the highest diesel replacement of 41.18, 42.31, and 64.21%, respectively, in the fuel blends. At higher-load conditions of 100 and 110%, the brake power on ethanol−diesel fuel blends was marginally higher than that of diesel. This was supplementary to the fact that the combustion efficiency of fuel blends improved and ignition delay decreased at higher-load conditions, as reported by different researchers.[31−33]

3.2.3. Fuel Consumption. The engine fuel consumption increased gradually with increase of brake load and was observed to be the highest at a brake load of 110% for all tested fuel blends. At the rated load condition, i.e., when the engine developed the rated power, the fuel consumption of the engine was 1.205 L/h on diesel and 1.432, 1.547, 1.488, 1.40, 1.35, 1.439, 1.390, and 1.622 L/h on DEE1, DEE12, DEE14, DEO1, DEO18, DEB1, DEB10, and DEB20, respectively (Table 5). The diesel fuel consumption was lowest at all of the brake mean effective pressures in comparison to the selected eight ethanol−diesel fuel blends (Figure 2). This was because of the reason that the calorific value of the tested ethanol−diesel fuel blends was less compared to diesel.

3.2.4. Brake-Specific Fuel Consumption (bsfc). The bsfc of the engine for diesel fuel at the rated load condition was 0.270 kg/kWh. For fuel blends DEE1, DEE12, DEE14, DEO1, DEO18, DEB1, DEB10, and DEB20, the bsfc was found to be 0.317, 0.350, 0.333, 0.309, 0.314, 0.0321, 0.319, and 0.376 kg/kWh, respectively (Table 6). Bsfc was found to increase with increase in ethanol substitution. Similar findings have been reported by different researchers.[34,35] As evident from Figure 3, the bsfc of the engine decreased gradually with increased brake load (BMEP) due to the reason that the engine brake power increased with increase in brake load.

3.2.5. Brake Thermal Efficiency. The engine brake thermal efficiency for diesel fuel at a BMEP of 5.4 bar (rated load) was 26.69%. The engine brake thermal efficiency of fuel blends DEE1, DEE12, DEE14, DEO1, DEO18, DEB1, DEB10, and DEB20 was 24.05, 21.98, 23.59, 24.49, 26.20, 27.47, 23.70, 23.94, 20.55, and 23.17 %, respectively. On an average, the brake thermal efficiency of aqueous fuel blends was higher as compared to diesel (Figure 4). This might have been because of the high heat of vaporization of alcohols resulting in excessive cylinder cooling and thus increase in brake thermal efficiency at higher-load conditions. A similar observation has been reported by other researchers.[36]

Table 6. Brake-Specific Fuel Consumption (bsfc) of the Test Engine for Selected Ethanol−Diesel Fuel Blends at Different Brake Mean Effective Pressures

brake load (%)	brake mean effective pressure (bar)		fuel types							
				diesel−ethanol−ethyl acetate fuel blends			diesel−ethanol−1-octanol fuel blends		diesel−ethanol−biodiesel fuel blends		
		diesel	200⁰[1:0.053:0.01]	190⁰[1:0.25:0.45]	185⁰[1:0.11:0.33]	200⁰[1:0.053:0.0052]	180⁰[1:0.11:0.15]	200⁰[1:0.053:0.14]	190⁰[1:0.11:0.62]	180⁰[1:0.25:1.54]
					Brake Specific Fuel Consumption (kg/kWh)					
no load		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20	1.1	0.705	0.748	0.760	0.739	0.737	0.748	0.751	0.742	0.764
40	2.2	0.428	0.440	0.449	0.443	0.430	0.431	0.400	0.452	0.456
60	3.25	0.324	0.362	0.410	0.368	0.358	0.327	0.324	0.382	0.397
80	4.3	0.285	0.340	0.392	0.353	0.327	0.328	0.329	0.340	0.405
100	5.4	0.270	0.317	0.350	0.333	0.309	0.314	0.321	0.319	0.376
110	5.9	0.272	0.307	0.355	0.334	0.312	0.303	0.317	0.325	0.366

3.2.6. Fuel Energy Input. The energy input to the engine was observed to increase with increase in BMEP and was found to be maximum at 110% brake load for all tested fuel blends (Figure 5). The energy input at the rated load for diesel and microemulsions DEE1, DEE12, DEE14, DEO1, DEO18, DEB1, DEB10, and DEB20 was found to be 50.05, 55.69, 60.43, 57.07, 54.83, 51.39, 56.82, 55.18, and 64.29 MJ/h, respectively. The highest input energy at the rated load condition was 64.2 MJ/h for diesel−ethanol−biodiesel fuel blend 180° [1:0.25:1.54]. This was because of the high fuel consumption of the engine associated with this fuel blend.

3.2.7. Unburnt Hydrocarbons. The observations revealed that the UBHC emission of the engine running on diesel fuel ranged from 0.01 to 0.21% at different brake mean effective pressures. The results revealed that the UBHC emission for diesel remained nearly constant upto 40% brake load, decreased between 40 and 60% load, and then increased with varying rate from 0.01 to 0.21% between a BMEP of 3.25 bar and 5.9 bar, respectively (Figure 6). Unburnt hydrocarbon (UBHC) emission from the exhaust of the engine for fuel blends DEE1, DEE12, DEE14, DEO1, DEO18, DEB1, DEB10, and DEB20 ranged from 0.03 to 0.20, 0.05 to 0.17, 0.02 to 0.19, 0.02 to 0.21, 0.01 to 0.18, 0.03 to 0.16, 0.06 to 0.20, 0.03 to 0.17, and 0.02 to 0.20%, respectively. At lower BMEP, ethanol−diesel fuel blends showed a much higher emission of UBHC in comparison to that of diesel. A similar finding of increase in UBHC emission for ethanol−diesel fuel blends has been reported by many researchers.[37,38] The UBHC content in the exhaust was slightly higher for diesel−ethanol−ethyl acetate and diesel−ethanol−1-octanol fuel blends, and lesser for diesel−ethanol−biodiesel blends compared to diesel. The higher ethanol proportion in ethanol−diesel blends resulted in increased UBHC emissions, and those with high biodiesel proportion generated less UBHC. This fact indicates that the presence of ethanol in the fuel blend was the reason for the increased UBHC emissions, and that biodiesel presence leads to reduction of UBHC.

3.2.7.1. Nitrogen Dioxide Emissions. The NO_2 emission from the exhaust of a diesel-fueled engine ranged from 23.4 to 92.4 ppm for different engine loading conditions. It increased to 92.4 ppm with a BMEP of upto 3.2 bar (i.e., upto 60% load) and thereafter decreased upto 110% load. The emission of NO_2 from the engine for selected fuel blends DEE1, DEE12, DEE14, DEO1, DEO18, DEB1, DEB10, and DEB20 was found to vary from 21.2 to 91.5, 17.0 to 67.8, 21.20 to 84.0, 18.5 to 90.5, 17.2 to 90, 25.2 to 98.4, 22.2 to 115.3, and 42.6 to 190.6 ppm, respectively, for different brake loads. Among all of the microemulsion fuels, the NO_2 emission was found to be highest for diesel−ethanol−biodiesel blends. This was probably because of the reason that biodiesel fuels had higher oxygen content and better combustion, leading to combustion temperature rise as reported by different researchers (Figure 7).[39−42]

3.2.7.2. Nitrogen Oxide Emissions. The emission of nitrogen oxide (NO) from the exhaust of a diesel-fueled engine expressed in ppm was in the range of 70.7−407.3 at varying BMEP. The emission of NO from the engine exhaust for fuel blends DEE1, DEE12, DEE14, DEO1, DEO18, DEB1, DEB10, and DEB20 was found to vary in the range of 72.4−397.6, 44.0−314.3, 56.0−430.2, 70.2−355.3, 70.2−360.6, 112.3−424.5, 90.2−627.3, and 100.36−590.3 ppm, respectively, between no load condition and 110 percent brake load.

From Figure 8, it is evident that at lower brake loads (upto 40%), the NO content in the exhaust was higher for diesel than for diesel−ethanol−ethyl acetate and diesel−ethanol−1-octanol
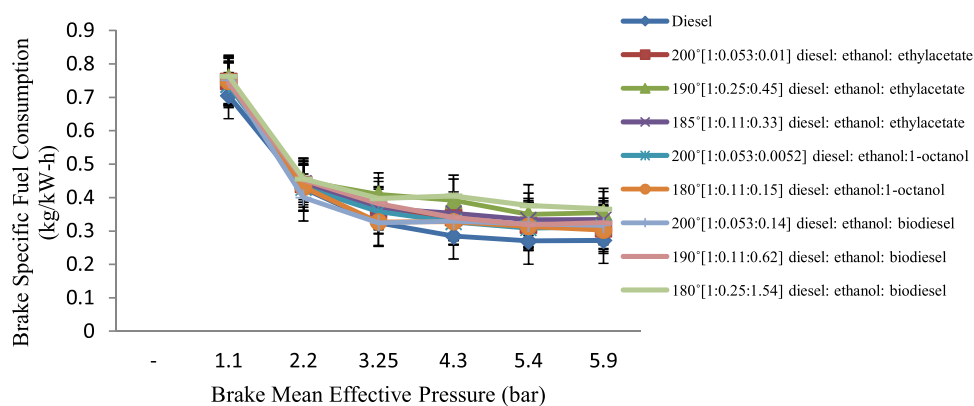
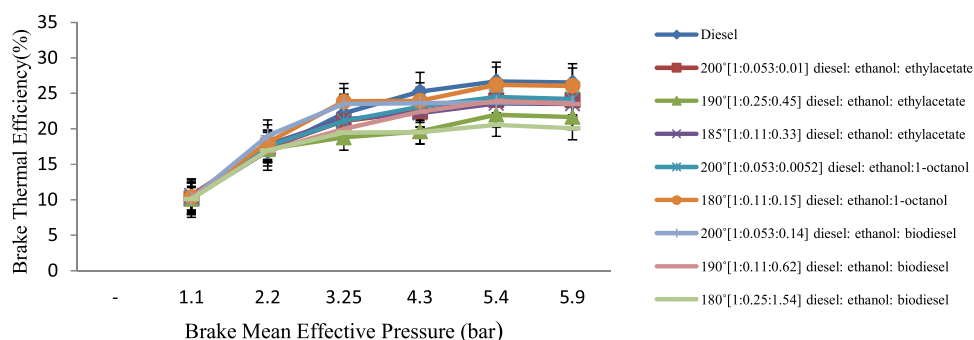**Figure 3.** Brake-specific fuel consumption (bsfc) of different blends at varying BMEP.

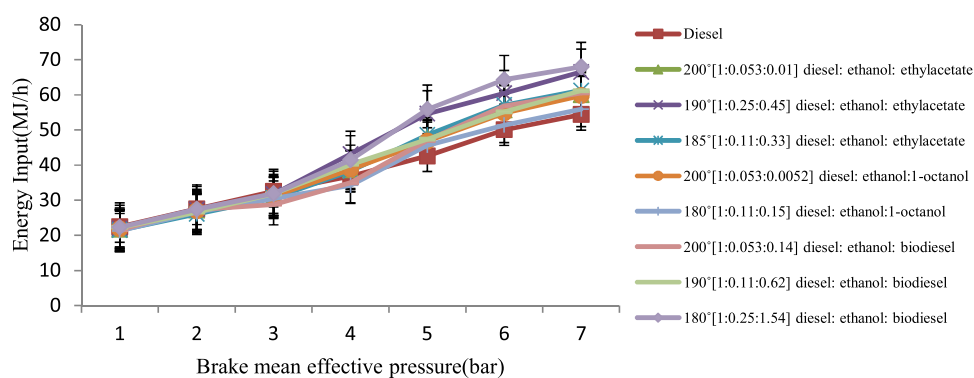**Figure 4.** Brake thermal efficiency of different blends at varying BMEP.

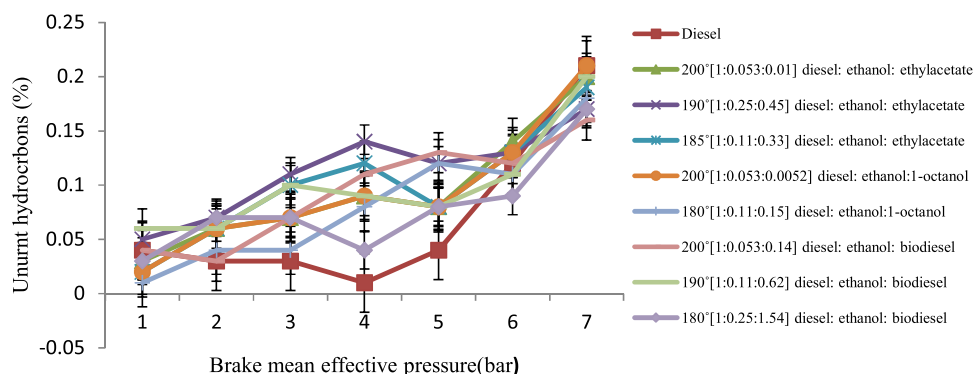**Figure 5.** Energy input of different blends at varying BMEP.

Figure 6. Unburnt hydrocarbon emission with different blends at varying BMEP.

emulsions, while it was found to be higher for the emulsions than for the diesel fuel at high BMEP (3.25−5.9 bar). There was an increase in combustion temperature due to the oxygen molecule present in ethanol, thereby resulting in increased NO_x
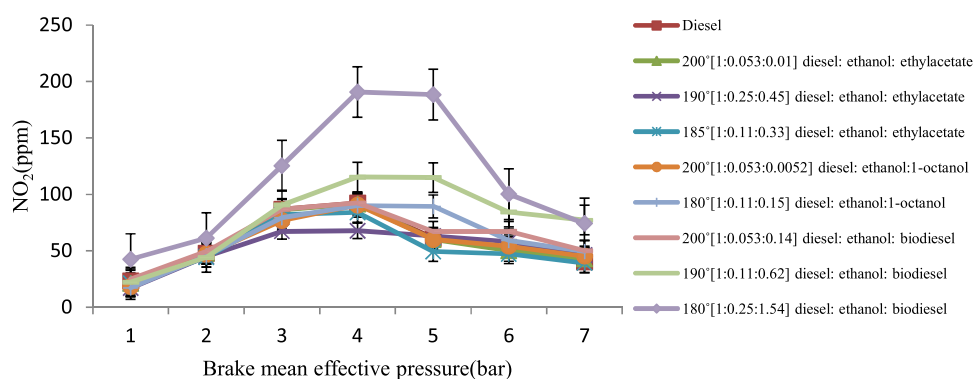
Figure 7. Nitrogen dioxide emission with different blends at varying BMEP.
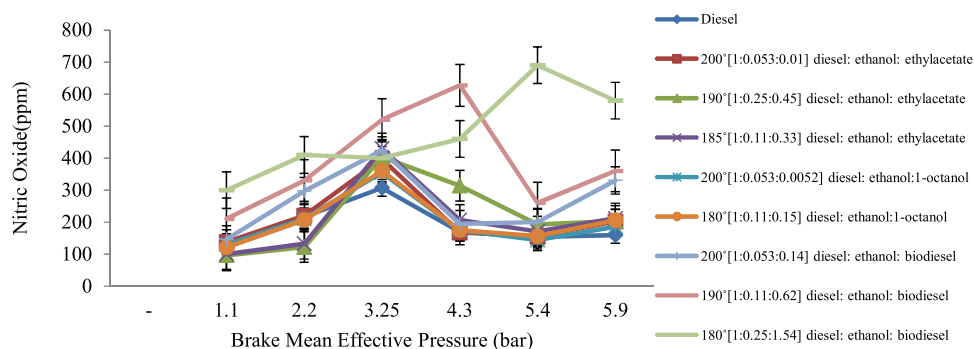

Figure 8. Nitrogen oxide emission with different blends at varying BMEP.

emissions.[43] The results also depict that nitric oxide emission on diesel−ethanol−biodiesel emulsions was higher compared to diesel and other fuel blends. It may be because of the reason that due to the higher oxygen content and improved combustion with biodiesel, the combustion chamber temperature can be expected to be higher, resulting in high NO_x formation in engines fueled with biodiesel.[44,45]

4. CONCLUSIONS

1-Octanol is the most effective surfactant compared to biodiesel and ethyl acetate for stabilization of ethanol−diesel fuel blends. The use of 1-octanol as surfactant allows use of a lower proof of ethanol in diesel−ethanol fuel blends, which increases the brake thermal efficiency and reduces the overall NO_x emissions. However, with the increase of ethanol proportion in ethanol−diesel blends, UBHC gets increased. The ethanol−diesel blends having diesel replacement upto 10% showed an engine performance similar to that of pure diesel. Based on the overall performance, it is imperative to suggest a diesel replacement of 5−10% with lower proof of ethanol by using 1-octanol as surfactant. In future, there is need to develop 1-octanol− ethanol−diesel−biodiesel blends and evaluate their performance for use as engine fuel.

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Notes

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