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An Analysis of Diesel Engine Output using Low and High Oxygen Content Soapnut Biodiesel Blends

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Abstract: *18 soapnut biodiesel-diesel mixes, some with soapnut oil, were tested in a diesel engine to see how oxygen concentration affected engine performance and emissions. The results were displayed using changing fuel oxygen concentration to account for fuel blends' considerable oxygen content differences. Fuel oxygen level between 1.8% and 3.0% generated the optimum engine performance, whereas 0.71% to 2.37% produced the best engine emissions. Considering engine performance and emissions, the recommended fuel oxygen concentration range is 1.80% to 2.37%. Thus, biodiesel mixed fuels with an oxygen content in the above range may be used in diesel engines with comparable emissions and performance. If blends include more biofuel, additional research is required to lower fuel oxygen levels to this optimal range. Additionally, utilizing proper additives in biodiesel mixed fuels may help achieve the aim, although more research is needed.*

Keywords: Soapnut biodiesel; diesel engine; engine performance; NO_X emissions; fuel oxygen content

I. INTRODUCTION

Due to scientific and technological advances, human lives have changed, increasing energy use. As demand for fossil fuels rises, traditional fossil fuel sources deteriorate faster. Using fossil fuels has also boosted greenhouse gas emissions, which has worried the environment. These factors have inspired a worldwide search for biomass-based fuels. Alternative fuels must be affordable, lucrative, and eco-friendly. Biodiesel is a viable diesel engine fuel that has increased in popularity in recent decades. It is primarily methyl and ethyl esters of fatty acids (triglycerides) formed by base-catalyzed transesterification from animal fats and edible and non-edible straight vegetable oils (SVOs) [1–3]. Biodiesel may be made from jatropha, karanja, rapeseed, soybean, palm, and other SVO feedstocks [2–7]. Renewable SVOs may replace fossil fuels, protect the climate, water, and soil, cut greenhouse gas emissions, and increase sustainability, regional development, and agriculture [2, 8]. Because of the great need for edible vegetable oils for cooking, rising countries like India and other South-East Asian nations typically produce biodiesel from non-edible oils. India produces biodiesel from jatropha, karanja, jojoba, castor, cottonseed, kokum, mahua, nahor, neem, ricebran, kusum, simarouba, soapnut, tumba, and other non-edible oils. These SVO sources include soapnut, a novel biofuel source with few biodiesel recipes. Soapnut, or Sapindus mukorossi Gaerth, is a deciduous Sapindaceae tree grown at 200–1500 meters in tropical and subtropical parts of Asia, America, and Europe [9]. The northern Indian Himalayas may potentially have it. Soapnut trees grow in thick clayey loam soil with 150–200 cm of annual rainfall [10]. The soapnut seed comprises 92% triglycerides and 23% oil. The soapnut kernel contains 42.7% oil [10]. Oleic (9Z-octadecenoic, C18:1) and eicosenoic (11Z-eicosenoic, C20:1) acids dominate soapnut oil [8]. Compared to other vegetable oils, soapnut oil has a high monounsaturated fatty acid content. Biodiesel derived from soapnut oil may have better oxidation stability due to its fatty acids [11].

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Biodiesel is renewable, biodegradable, and non-toxic like diesel. Biodiesel is better than diesel fuel due to its higher flash point, lower volatility, and greater lubricity [2, 12–15]. Biodiesel is sulfur-free, has 10%–12% oxygen by weight, and has less aromatic chemicals. Oxygen increases the oxidation of incompletely burned hydrocarbons generated during combustion [16, 17]. Biodiesel reduces PM, HC, and CO emissions. Increasing oxygen concentration in biodiesels increases NOx emissions, which is concerning [18–22]. Biodiesel has higher cetane number, viscosity, sound velocity, and bulk modulus than diesel. These properties cause a short ignition delay and early fuel injection [23, 24]. Viscosity is biodiesel's main downside [7, 25–29]. Higher viscosity biodiesel causes piston head carbon deposits, poor atomization, poor cold-flow, injector coking, filter clogging, and other issues [2, 23]. Other downsides of biodiesel include higher brake specific fuel consumption (BSFC), longer combustion duration, engine power losses, lower volatility, heating value, energy density, heat release, and pressure rise. Chauhan et al. [30] observed that jatropha biodiesel blends had higher NOx emissions, lower HC, CO, CO2, and smoke emissions, and lower brake thermal efficiency (BTE) and higher BSFC than diesel fuel. Additionally, Altaie et al. [31] discovered that improved biodiesel mixed fuel had higher BSFC and lower braking torque than diesel fuel due to its lower calorific values. Poor ignition increased CO, HC, and NOx engine emissions. Alptekin [32] found that biodiesel and biodiesel blends decreased CO and HC emissions, increased NOx and CO2 emissions, and increased BSFC in diesel engines. These experiments and others that employ biodiesel as fuel in compression ignition (CI) engines show that its higher NOx emissions from combustion, largely due by its higher oxygen content, are the principal barrier to its commercial manufacturing. In order to guarantee similar engine performance and acceptable engine emission characteristics, it is necessary to assess the appropriate range of oxygen concentration in biodiesels and biodiesel mixed fuels.

The present research turned soapnut oil into biodiesel, which was blended with diesel fuel in the right volumetric ratios and used in a CI engine. In order to identify the ideal range of oxygen concentration in biodiesel fuel for attaining the greatest engine performance and emissions, the current effort aims to investigate the impact of fuel blends' oxygen content on engine performance and emission characteristics. In order to lower the oxygen concentration in fuel blends to the ideal range, the function of parent vegetable oil as an addition to biodiesel-diesel blends was also investigated.

II. MATERIALS AND METHODS

Fuel Sample Preparation

The present experiment used soapnut oil (SO) as biofuel. SO was chosen because it is non-edible, cheap, and a new biofuel. Base-catalyzed transesterification and plain SO produced soapnut biodiesel (SB). SB was made in a 10-liter biodiesel reactor (Gobind Machinery Works, New Delhi). Biodiesel was prepared by adding five liters of filtered SO to the reactor. Then, 100 g KOH (base catalyst) and 1 liter (20% by vol.) methanol were mixed. The reactor received the reagent mixture after preheating the SO slightly above room temperature. The reaction temperature was 60°C and the stirrer speed 750 rpm. After 90 minutes of transesterification, the product settled for six hours. Raw biodiesel was removed from the reactor bottom after glycerol. Raw biodiesel settled for three hours after three water washes. Around 3.5 liters of pure SB were generated after washing, settling, and moisture removal.

The prepared SB was blended with diesel in volumetric basis percentages of 10%, 15%, 20%, 25%, 30%, and 40% to make SB10, SB15, SB20, SB25, SB30, and SB40. Also introduced was SB100, 100% biodiesel. SB10-SO2.5 (10.0% by vol. of SB, 2.5% by vol. of parent SVO, and the rest diesel), SB10-SO5, SB15-SO2.5, SB15-SO5, and others were created by adding parent vegetable oil (SVO) in small volume percentages of 2.5%, 5.0%, and 10.0% to SB10, SB15, SB20, and SB25 biodiesel blends. Therefore, 18 gasoline blends—SB10, SB10-SO2.5, SB10-SO5, SB10-SO10, SB15, SB15-SO2.5, SB15-SO5, SB15-SO10, SB20, SB20-SO2.5, SB20-SO5, SB20-SO10, SB25, SB25-SO2.5, SB25-SO5, SB25-SO10, SB30, and SB40—were produced for Using the final biofuel blends' oxygen concentration, the volumetric proportions of SB and SO were considered.

Many traditional ASTM methods were used to characterize the 18 fuel blends. According to fuel characterisation data, fuel blends' density, viscosity, cloud point, and pour point increased with oxygen content. All fuel blends had densities between 837 and 855 kg/m3 and viscosities between 3.05 and 4.16 cSt. The pour and cloud points were 3.5°C to 4.9°C and 7.0°C to 12.6°C, respectively. The calorific value of fuel blends decreased as oxygen percentage rose. Calorific value ranged from 40.74 to 42.50 MJ/kg. Critical study of the data showed that all fuel blends had physico-chemical

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properties comparable to diesel. After fuel characterisation, carbon, hydrogen, and oxygen were measured in fuel blends. Tables 1 and 2 indicate elemental analysis' fuel characterisation and oxygen content % for each fuel combination.

Table 1. Fuel characterisation results for SB blends.

Property	SB10	SB15	SB20	SB25	SB30	SB40	SB100	Diesel	ASTM test no.
Density (kg/m^3)	837.0	839.3	842.7	843.9	849.9	853.0	870.0	835.0	D4052
Viscosity at 40°C (cSt)	3.05	3.10	3.17	3.35	3.61	4.11	4.86	2.83	D445
Calorific value (MJ/kg)	42.50	42.46	42.38	42.10	41.74	40.89	38.24	44.62	D240
Flash point (°C)	91	96	105	108	120	124	175	70	D93
Cloud point (°C)	7.00	7.50	8.40	9.20	10.70	11.50	13.50	6.40	D2500
Pour point (°C)	3.50	3.70	4.00	4.20	4.40	4.70	5.10	3.00	D97
Cetane index	48.38	48.45	48.57	48.66	48.81	48.95	51.40	48.00	D613

Table 2. Percentage of oxygen content in SB blends.

Fuel blend no.	Fuel blend name	% by volume			Oxygen (% by wt.)
		SB	Diesel	SO	
1	SB10	10	90.0	0	0.961
2	SB10-SO2.5	10	87.5	2.5	1.210
3	SB15	15	85.0	0	1.240
4	SB15-SO2.5	15	82.5	2.5	1.469
5	SB10-SO5	10	85.0	5.0	1.499
6	SB20	20	80.0	0	1.686
7	SB15-SO5	15	80.0	5.0	1.748
8	SB10-SO10	10	80.0	10.0	1.809
9	SB25	25	75.0	0	2.010
10	SB20-SO2.5	20	77.5	2.5	2.060
11	SB15-SO10	15	75.0	10.0	2.309
12	SB25-SO2.5	25	72.5	2.5	2.329
13	SB20-SO5	20	75.0	5.0	2.377
14	SB30	30	70.0	0	2.410
15	SB20-SO10	20	70.0	10.0	2.648
16	SB25-SO5	25	70.0	5.0	2.830
17	SB40	40	60.0	0	3.070
18	SB25-SO10	25	65.0	10.0	3.602

For future reference, fuel blends are rearranged based on rising oxygen concentration, and their blend number is allocated appropriately (Table 2). According to the CHN-O study, there is a significant difference in the oxygen concentration across all 18 fuel mixes, measuring 78.23%. Consequently, it seems sense to base a comparative evaluation of the impact of SB mixes on engine performance on differences in oxygen percentage.

Experimental Setup

The performance and emission characteristics of the 18 fuel mixes were assessed in the current study using a single-cylinder, four-stroke, water-cooled diesel engine. An eddy current dynamometer was connected to the test engine, and a load console managed loading. Diesel and SB mixes were supplied to the engine independently using a two-way fuel

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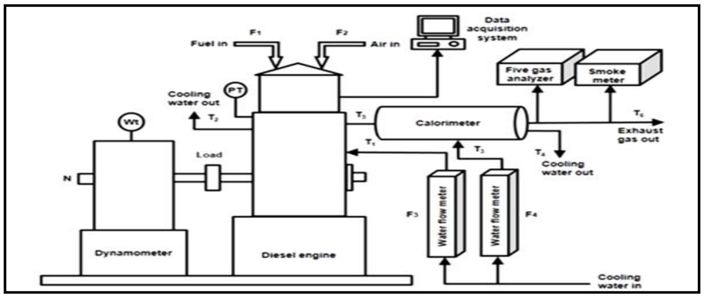
delivery line and two distinct fuel tanks. The test engine was equipped with an AVL 437 smoke meter and a five gas analyzer (AVL Digas 444) to measure emissions. Enginesoft LV program, which was installed on a computer, ran the complete engine test. Figures 1 and 2 show a schematic design and a picture of the experimental engine configuration, respectively. Table 3 displays the test engine's specifications.



F1: Fuel injection pressure sensor, F2: Air flow measuring, F3: Water flow meter to engine, F4: Water flow meter to calorimeter, T1: Cooling water inlet temperature to engine, T2: Cooling water outlet temperature from engine, T3: Cooling water inlet temperature to calorimeter, T4: Cooling water outlet temperature from calorimeter, T5: Exhaust gas inlet temperature to calorimeter, T6: Exhaust gas outlet temperature from calorimeter, PT: Piezo sensor, N: rpm pick up and TDC encoder.

Figure 1. Schematic diagram of the experimental engine setup.

Figure 2. Photograph of the experimental engine setup.

Table 3. Specifications of the test engine.

Variable	Specification
Make	Kirloskar, TV1 model
Type	4-stroke, single-cylinder, water cooled, direct injection, naturally aspirated
Dynamometer	Eddy current, water cooled, with loading unit
Bore × Stroke	87.5 mm × 110.0 mm
Compression ratio	17.5
Connecting rod length	234 mm
Displacement	0.661 litre
Rated power	5.2 kW
Rated speed	1500 rpm
Fuel injection type	Single barrel F.I. pump, inline fuel injector
Injection timing	23° BTDC
Inj. opening pressure	20.5 MPa

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Injector hole dia.	3 × 0.288 mm
Orifice dia.	20 mm
Dynamometer arm length	185 mm
Rotameters	Engine cooling 40–400 LPH, Calorimeter 25–250 LPH

III. RESULTS AND DISCUSSION

Although essentially equivalent, performance and emission data varied widely with fuel mix oxygen percentages. Thus, these factors must be compared on one platform. Parameters are often represented as non-dimensionalized parameters to align their coordinate axes. Since diesel was the foundation fuel for all fuel blends in the current research, each engine performance and emission parameter for a fuel mix was represented as a non-dimensionalized parameter for diesel. This non-dimensionalized metric compares a fuel mix's performance or emission parameters to diesel fuel. Thus, a fuel blend's ith parameter is:

$$(\beta_{specific\ biodiesel\ blend})_i = i_{specific\ biodiesel\ blend} / i_{diesel} \quad (1)$$

Eq. (1) illustrates that i is the specified engine performance or emission parameter, whereas βi is the non-dimensionalized parameter for the ith parameter of a particular fuel mix.

Effect of Fuel Oxygen Content on Engine Performance Parameters

Based on experiments with the fuel blends under consideration, Figure 3 shows the variations of various engine performance parameters, such as BTE, brake specific energy consumption (BSEC), and exhaust gas temperature (EGT), against different percentages of oxygen content in the fuel blends. The results are presented along with any necessary discussions.

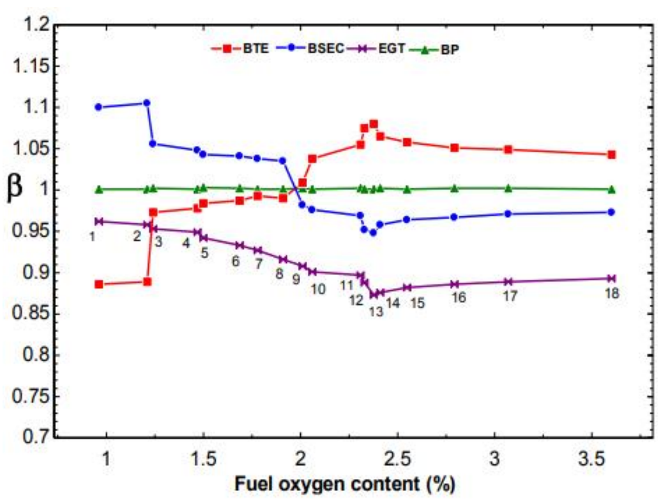

Figure 3. Variation of $\beta_{engine\ performance\ parameters}$ with fuel oxygen content.

Brake Thermal Efficiency

BTE, a critical engine performance statistic, measures shaft power output. This also defines how successfully the engine turns fuel's chemical energy into mechanical power. SB blends had a BTE higher than diesel at 1.97% oxygen content. Additionally, $(\beta)TE$ increased with oxygen percentage in SB fuel blends, reaching 2.37%. Rising oxygen percentages lower heating value and consume less fuel energy to create braking power [33, 34]. Additionally, gasoline mixtures with oxygen level above 1.97% exhibited higher BTE than diesel. More oxygen generates a more complete combustion and higher BTE [33, 35–37]. Second, biodiesel blends' higher density than diesel delivers more fuel during combustion, compensating for their lower heating value and higher BTE [33, 35].

Brake Specific Energy Consumption

In SB blends, $(\beta)SEC$ decreased as oxygen concentration increased to 2.37%. Fuel blends with oxygen concentrations above 1.97% exhibited lower BSEC than diesel. More oxygen may promote complete combustion and reduce BSEC [33]. Additionally, fuel mixtures with oxygen concentrations above 2.37% showed a little increase in $(\beta)BSEC$ compared to diesel. These blends' higher density and viscosity may have produced insufficient atomization and inefficient combustion, which overshadowed the heating value enhancement and increased fuel consumption [30, 33, 38, 39]. These studies indicate that gasoline mixtures with oxygen concentrations between 1.975% and 2.370% have lower BSEC than diesel.

Exhaust Gas Temperature

$(\beta)GT$ was shown to decrease when the oxygen content for SB blends increased up to 2.37%. The combination may have reached stoichiometric conditions more quickly since the stoichiometric fuel-air ratio rose as the oxygen fraction in fuel blends increased [40]. However, $(\beta)GT$ rose over the oxygen percentage of 2.37%, which might be the result of better combustion brought on by the fuel blends' greater oxygen content [41, 42]. Furthermore, among the related fuel mixes, fuel blend number 13 had the lowest $(\beta)GT$, making it the most preferred fuel blend. Therefore, regardless of fuel type, the optimal engine performance was found for oxygen concentration between 1.8% and 3.0% after taking into account all engine performance factors. For gasoline blends, the BSEC was in the lowest range while the BTE was in the highest range.

Effect of Fuel Oxygen Content on Engine Emission Parameters

CO, HC, NOx, smoke opacity, and other exhaust pollutants are the main problems preventing CI engines from operating well. According to published research, biodiesels emit much less CO and HC than diesel [30, 43, 44]. However, compared to diesel, biodiesel modestly increases NOx emissions. Furthermore, one potential solution to lower NOx emissions is the use of parent vegetable oil as an ingredient in biodiesel blends [45]. Figure 4 displays the non-dimensionalized emission parameters $(\beta)O$, $(\beta)HC$, $(\beta)CO2$, $(\beta)OX$, and $(\beta)PM$ for SB blends with regard to a rise in oxygen content. A thorough description of the findings follows.

CO emissions

It was found that the CO emissions steadily decreased as the oxygen content in the fuel mixes increased. This could be because mixes of biodiesel have less carbon than diesel [46, 47]. Therefore, each carbon atom has a greater chance of finding two oxygen atoms to bond to generate CO2 when there is less carbon in the fuel. This result is consistent with that of Azad et al. [48], who observed decreased CO emissions in every instance when compared to diesel using a variety of soybean and waste cooking oil biodiesel mixes. Reduced CO emissions may also result from the fact that during combustion there The performance of a diesel engine 4582 may be impacted by the oxygen level of soapnut biodiesel-diesel blends. This is because the presence of fuel oxygen in the blends may diminish the likelihood of a rich fuel zone forming, which in turn reduces CO emissions [46]. Additionally, compared to diesel, there was a significant decrease in CO emissions for gasoline mixes with an oxygen level of greater than 2.37%.

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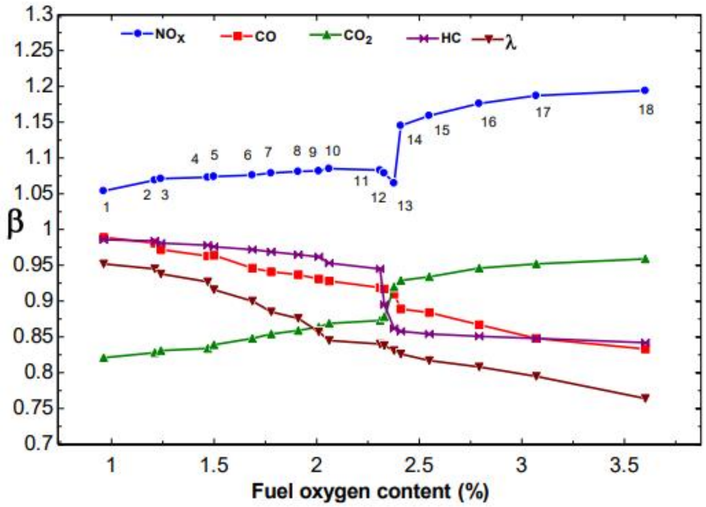

Figure 4. Variation of exhaust emission parameters with fuel oxygen content.

CO2 Emissions

Figure 4 illustrates how CO2 emissions rose as the amount of oxygen in SB mixes increased. All of the fuel mixes had lower CO2 emissions than diesel. This is consistent with Dubey and Gupta's findings [49]. Because biodiesels are low carbon fuels with a lower elemental carbon to hydrogen ratio than diesel, this is explained [47, 50]. The CO2 emissions from fuel mixes with an oxygen concentration below 2.32% were relatively lower. However, all of the fuel mixes showed a rapid increase in CO2 emissions at these oxygen percentages, which might be related to the fuel blends' increased oxygen content [51].

HC Emissions

Research on CI engines shown that, as compared to diesel, engines using biodiesel fuel mixes produced less HC emissions [52]. Figure 4 shows that as the amount of oxygen in the fuel mixes increased, HC emissions decreased. Since over-mixing is the main cause of HC emissions, all fuel mixes had lower HC emissions than diesel. Both ignition delay and air-fuel mixing throughout the combustion stage are closely associated with overmixing [53–55]. Complete combustion and lower HC emissions were caused by both improved atomization and a shorter ignition delay. Additionally, it was noted that HC emissions were superior than those of other fuel blends at oxygen percentages greater than 2.37% (blend numbers 13–18), with fuel blend number 18 exhibiting the lowest HC emission.

NOx Emissions

Figure 4 shows that for all SB mixes, NOx emissions rose as the oxygen % rose and are greater than those of diesel. When the oxygen percentage grew over 2.37%, as it did for blend number 13, NOx emissions increased even further. Advanced injection time, greater CN, higher viscosity, oxygen present, and a shorter ignition delay are some potential causes of this [56,57]. The initiation of combustion is advanced by improving the timing of injections. This might raise the cylinder's peak temperature and speed up the generation of NOx [56,57]. In addition, this causes a prolonged residence period, which permits the creation of NOx to continue. Additionally, biodiesel fuel mixes with greater CN have shorter ignition delays, which speeds up the commencement of combustion. This causes the temperature in the cylinder to rise for a much longer period of time, giving nitrogen more opportunity to react with oxygen and produce additional NOx emissions [58]. In line with existing research, it was found that gasoline mixes 1 and 18 had the lowest and greatest NOx emissions, respectively [59].

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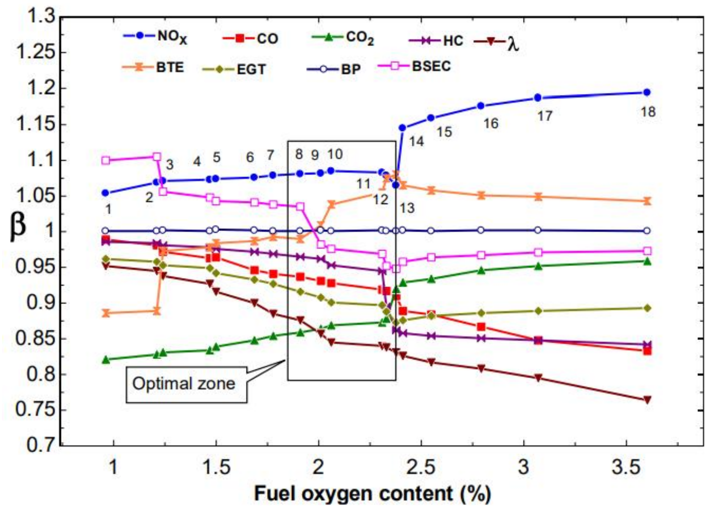

Figure 5. Combined effect of βemission parameters and βengine performance parameters with fuel oxygen content.

Combined Effect of Engine Performance with Emissions

It was clear from the engine performance study that the optimal engine performance was achieved with an oxygen content of 1.8% to 3.0%, with the BTE in the maximum range and the BSEC in the lowest range for fuel blends. However, according to emission analysis data, this area was pleased by the CO, HC, and smoke opacity patterns, which all steadily declined as the oxygen level rose. This might be because increased oxygen content causes more thorough burning. This is consistent with previous research [60, 61]. The NOx and CO2 emissions values, on the other hand, indicated an area of interest ranging from 0.71% (lowest) to 2.37%. Therefore, the ideal oxygen concentration zone for each fuel type was assessed while taking emissions, engine performance, and restrictions into account. The results are shown in Figure 5. This ideal zone was determined to have an oxygen level ranging from 1.80% to 2.37%. Fuel mixes in this range, namely blends 8–13, demonstrated reduced exhaust pollutants and improved engine efficiency. Fuel blend number 13, which has 2.37% oxygen, 84.88% carbon, and 12.56% hydrogen, could be the best in this range. It was determined to have a molecular weight of 275.02 kg/kmol and a chemical formula of $C19H33.8O0.4$.

IV. CONCLUSION

The present study examined how SB-diesel mix fuel oxygen concentration affects CI engine emissions and performance. According to research and statistics, the engine ran most efficiently when the fuel mixes' oxygen content was 1.8% to 3.0%. For all biodiesel blends, the BTE was greatest and the BSEC was lowest within this oxygen concentration range. Biodiesel blends had superior BTE and BSEC than diesel at oxygen levels over 1.8%. Emission experiments under the optimal loading circumstances showed that CO, HC, and smoke opacity trends decreased as fuel mix oxygen concentration rose. All of these contaminants were lower in SB blends than diesel. In contrast, NOx and CO2 emissions data showed that fuel mix oxygen concentration should be between 0.71% (the lowest) to 2.37%. The optimal oxygen content range for the specified gasoline blends was 0.71% to 2.37%, considering NOx and CO2 emissions. Considering emissions and engine performance, the optimal oxygen content range is 1.80%–2.37%. Best fuel mixes were 8–13, which enhanced engine performance and lowered pollutants. Its increased engine performance and emissions results Fuel blend 13 may be the finest in this range. Thus, biodiesel blends with a fuel oxygen content between 1.80% and 2.37% may be used as diesel engine fuel with equivalent engine performance, NOx and CO2 emissions, and lower CO, HC, and smoke emissions. The recent study shows that this range of oxygen content limits the biofuel component in the fuel mix to 25%. Thus, further research is required to increase the mixed fuel's biofuel content beyond 25% while maintaining a fuel oxygen concentration between 1.80% and 2.37%. Future research may examine biodiesel mixed fuel additives that drop oxygen levels to the required range.

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