Experimental investigation to improve performance and emission characteristics of a diesel engine by using n-butanol as additive to the biodiesel-diesel blends

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Abstract. Fossil fuels are non-renewable resources and are limited in supply. The combustion of these fuels produces environmental pollution with the release of dangerous gases like Nitrogen oxides, Carbon monoxide and Carbonaceous soot. In this sense, fuel like biodiesel produced from vegetable oils can be considered as a better alternative to the fossil fuels. For this study, waste cooking oil biodiesel is used. In this work, the effect of addition of n-butanol on the performance and emission characteristics of diesel engine running at the speed of 2300 rpm is investigated. The biodiesel is prepared by transesterification process using KOH as catalyst. n-Butanol is added to B20 blend in varying volume percentages of 5, 10 and 15 to evaluate its effect on performance and emission characteristics. It is observed that BU15 possesses better performance characteristics among n-butanol blends compared to B20 with an average decrease of 18% in BSFC and increase of 21% in BTE at high loads. The experimental results showed that NOx and CO2 emissions were further reduced by 19% and 28% respectively with the addition of butanol. There has been reduction in smoke emissions by 4.7% but an increase of 22% in HC emissions for n-butanol blends.

Keywords. Biodiesel, Transesterification, Additive, Emission, n-Butanol

1. Introduction
The major problem faced with the usage of petroleum fuels is the environmental pollution. The pollution is mainly contributed by automobiles [1]. Diesel engines play an important role in transportation sector due to its fuel economy and high brake thermal efficiency. But, they emit higher amount of Nitrogen oxides and soot particulates. Vegetable oils, which are the sources of renewable energy are considered to be better alternative to diesel fuel since they are eco-friendly and possess similar properties to that of diesel [2-3]. The main health problems associated with reusing of cooking oil include acidity and heart diseases. The waste cooking oil which is abundant and cheap can be used.
as feedstock in biodiesel production [4]. Hence, research is being conducted to test the feasibility of usage of various edible/non-edible biodiesel in diesel engine. Bio-fuel produced from these oils is generally non-toxic and free from sulphur content [5].

Biodiesel is a long chain methyl or ethyl ester which can be produced by various processes like pyrolysis, transesterification and micro-emulsions. In the process of transesterification, the triglycerides present in the oil react with alcohol in the presence of catalyst to form fatty acid alkyl ester (biodiesel) and glycerin [6]. In general, fuel additives enhance the properties like density, viscosity and solubility etc. to improve the performance and reduce the exhaust emissions. With the addition of additives to the biodiesel-diesel blends, biodiesel standards are maintained and engine performance is improved. Additives are chosen based on various properties like viscosity, miscibility and calorific value etc. Some of the fuel additives are methanol, ethanol and butanol [7-8]. The properties of additives are given in table 1.

| Properties     | Methanol | Ethanol | n-Butanol |
|----------------|----------|---------|-----------|
| Cetane number  | 5        | 8       | 25        |
| Heating value (MJ/kg) | 22.7     | 26.8    | 33.1      |
| Density (kg/m$^3$) | 790      | 788     | 810       |

Vignesh D and Srihari S [9] carried out performance and emission analysis on diesel engine by using mixture of cottonseed oil and sunflower oil biodiesel blended with diesel. It is reported an improvement in performance and reduction in exhaust emissions. It is concluded that a maximum of 20% blend could be used in the engine without any modifications. Srihari S et al. [10] conducted the experiments on diesel engine using cotton seed biodiesel-diesel blends with diethyl ether as additive. It is reported that smoke emissions are reduced and brake thermal efficiency is improved. Ashraf Elfasakhany and Abdel-Fattah Mahrous [11] investigated the effects of butanol-methanol-gasoline fuel blends on the performance and emission characteristics of petrol engine. It is reported that CO$_2$ emissions are reduced and CO, HC are increased. It is concluded that dual alcohol blends could increase performance and lower the emissions. It is recommended to use single alcohol if lower rate of alcohol is preferred. Gokhan Tuccar et al. [12] conducted the experiments to analyze the effects of n-butanol addition to microalgae biodiesel blends on the performance and emissions of a diesel engine. It is reported that emission characteristics are improved. It is concluded that butanol could be used as additive to biodiesel blends in diesel engines to reduce the emissions. Pushparaj T and Ramabalan S [13] conducted the experiments on diesel engine with ethanol-cashew nut shell biodiesel blends and it is found that there is remarkable reduction in NOx emissions by 57%. It is concluded that 10% addition of ethanol resulted in effective performance. Puneth Kumar Reddy V et al. [14] investigated the effect of antioxidants on emission characteristics of diesel engine run with waste cooking oil biodiesel. It is reported that greater reduction in NOx and HC emissions is noticed with the usage of 2, 6-ditert-butyl-4-methylphenol to biodiesel-diesel blend B20. Prabakaran B and BakriOsman [15] carried out emission analysis on diesel engine by investigating the effect of butanol addition to diesel. It is reported that the average reduction of NO, and CO emissions is 30% and 75% respectively.

The above studies suggest that fuel additives reduce exhaust emissions but limited research is done on emission analysis using n-butanol as additive. In this work, investigation is carried-out to analyse the effect of butanol addition on the performance and emission characteristics of diesel engine. The biodiesel is produced from waste cooking oil. n-Butanol is chosen as additive because of its higher cetane number around 25, good miscibility characteristic and higher heating value around 33100 kJ/kg compared to methanol and ethanol. Butanol is blended with B20 in various proportions of 5, 10 and 15% by volume.
2. Methodology

2.1. Preparation of biodiesel

The biodiesel is produced from waste cooking oil by transesterification process in which about 4g of potassium hydroxide (0.5% w/w of oil) is dissolved in 200 ml of methanol (25% v/v of oil) for the preparation of methoxide. After stirring for 30 min, the mixture is transferred into the beaker containing 800 ml of waste cooking oil and heated to 60℃ for 2 hours at constant stirring speed. Later, it is kept undisturbed till glycerine gets precipitated. Then, biodiesel is separated and water washed. It is heated finally to remove any water particles.

2.2. Experimental Setup and Procedure

The experiments are performed on a single cylinder, four-stroke diesel engine. The schematic layout of experimental setup and engine test bed are shown in figure 1 and figure 2 respectively. A crank angle encoder which has resolution of 0.1º and a pressure transducer are mounted on crankshaft and cylinder head respectively to obtain Pressure-Crank angle data. Table 2 shows the test engine specifications and the test fuels are given in table 3. The experiments are performed at constant speed of 2300 rpm from no load up to the maximum load of 12 Nm with 20% step increment. Exhaust emissions such as NOx, HC and CO\textsubscript{2} are measured by using MEXA-584L five gas analyser and Smoke concentration is measured by using AVL 415SE smoke meter. Specifications of the gas analyser and smoke meter are given in table 4. The properties of blended fuels diesel, waste cooking oil biodiesel (WCOB) and n-butanol are given in table 5. The uncertainties of measured parameters are given in table 6. A sample calculation of uncertainty is presented in appendix.
Table 2. Test Engine Specifications.

| Parameter               | Specifications |
|-------------------------|----------------|
| Model                   | Greaves GL-400 |
| Maximum power output    | 5.5 kW         |
| Bore                    | 63 mm          |
| Stroke                  | 86 mm          |
| Displacement            | 395 cm³        |
| Compression ratio       | 18:1           |

Table 3. Test Fuels.

| Blend | Blend Ratios               |
|-------|----------------------------|
| B20   | 20% biodiesel, 80% Diesel  |
| BU5   | 5% n-butanol, 95% B20      |
| BU10  | 10% n-butanol, 90% B20     |
| BU15  | 15% n-butanol, 85% B20     |

Table 4. Specifications of the Five gas analyzer and Smoke meter.

| Model               | Pollutant | Range             | Resolution |
|---------------------|-----------|-------------------|------------|
| MEXA 584L NOx       | 0-5000 ppm vol. | 1 ppm vol.       |
| MEXA 584L HC        | 0-20000 ppm vol. | 1 ppm vol.       |
| MEXA 584L CO2       | 0-20% vol.    | 0.02% vol.        |
| Smoke Meter AVL 415SE Smoke | 0-10 FSN | 0.001 FSN         |

Table 5. Fuel Properties.

| Properties          | Diesel | WCOB | n-Butanol |
|---------------------|--------|------|-----------|
| Density (kg/m³)     | 820    | 910  | 810       |
| Kinematic Viscosity (cSt) (40°C) | 2.3    | 30.8 | 3.6       |
| Calorific Value (kJ/kg) | 43500  | 37170| 33100     |
| Cetane number (CN)  | 52     | 33   | 25        |
| Flash point (°C)    | 46     | 256  | 35        |
| Fire point (°C)     | 52     | 268  | -         |

Table 6. Uncertainties of Measured Parameters.

| S.No | Parameter | Percentage Uncertainty |
|------|-----------|------------------------|
| 1    | BP        | ±1.02%                 |
| 2    | FC        | ±1.00%                 |
| 3    | BTE       | ±1.43%                 |
| 4    | HC        | ±0.167                 |

3. Results and discussion

3.1. Performance Characteristics

3.1.1. Brake Specific Fuel Consumption (BSFC). The variation in brake specific fuel consumption with brake power for butanol-biodiesel blends is shown in figure 3. With increase in load, specific fuel consumption has been reduced which could be due to improvement in combustion because of higher in-cylinder temperatures obtained. It is observed that, with increase in butanol concentration, brake specific fuel consumption is reduced by at higher load of 10Nm for butanol blends compared to B20. This could be because of lesser viscosity of blended fuel butanol which reduced the fuel viscosity.
further and improved the spray quality for effective combustion. The fuel consumption is least for neat diesel. An average reduction of 15%, 10% and 18% is achieved for BU5, BU10 and BU15 respectively at higher loads compared to B20. It is noticed that B20 possessed the higher BSFC among all the test fuels.

![Figure 3. Variation in BSFC with Brake Power.](image)

3.1.2. Brake Thermal Efficiency (BTE). The variation in brake thermal efficiency with brake power for various fuels is shown in figure 4. Brake thermal efficiency is observed to reduce when biodiesel blend is used which could be due to its lower calorific value. But, the addition of butanol has resulted in better combustion leading to higher thermal efficiency because of reduction in viscosity and improvement in the spray characteristics. An increase of 21% in BTE is observed for BU15 while it is 14% and 13% for BU5 and BU10 when compared to B20. It is observed that the brake thermal efficiency for BU15 is almost equal to that of diesel fuel at maximum load of 12 Nm.

![Figure 4. Variation in BTE with Brake Power.](image)

3.1.3. Exhaust Gas Temperature (EGT). Figure 5 shows the variation in exhaust gas temperature with brake power for various fuels. The reasons for higher exhaust gas temperature could be higher ignition delay and poor atomization which delay combustion. It is observed that EGT is increased with increase
in butanol concentration. At high load, BU15 possessed higher exhaust gas temperature of 502°C whereas it is 485°C for neat diesel. The lower heating value of n-butanol compared to B20 and higher latent heat of vaporization of butanol (585 kJ/kg) has led to the increase in exhaust gas temperature.

3.2. Emission Characteristics

3.2.1. Nitrogen Oxides. The variation in Nitrogen oxides (NOx) with brake power for various fuels is shown in figure 6. The formation of Nitrogen Oxides is based on the combustion temperature inside the cylinder. It is observed that the NOx emissions are increased with brake power due to rise in temperature. The NOx emissions indicated a decrease when butanol is added to B20 in different proportions because of reduction in combustion temperature and higher heat of evaporation of butanol around 585kJ/kg. Since butanol possess lower energy content, it could lead to ignition delay which reduces NOx formation. The NOx emissions are reduced by 35.8% and 31% for BU15 compared to diesel and B20 respectively at maximum load. The emissions are highest for diesel with 648 ppm at maximum load.
3.2.2. Hydrocarbons. The variation in unburned hydrocarbon (HC) emissions with brake power for various fuels is as shown in figure 7. Incomplete burning of fuel leads to HC emissions. Incomplete combustion could be because of ignition timing delay and rich mixture supply. It is observed that addition of butanol to B20 has increased HC emissions because of its lower cetane number which could reduce the combustion efficiency. Also, lower combustion temperatures may result in increase of HC emissions. It is observed that BU15 gives higher HC emissions due to the rich mixture. The rich mixture could be because of injector leakage or excess fuel pressure. The HC emissions are lesser for neat diesel fuel followed by BU5. For BU15, HC emissions are increased by 27% and 40% as compared to B20 and diesel respectively at maximum load.

![Figure 7. Variation in Hydrocarbons with Brake Power.](image)

3.2.3. Smoke Concentration. The variation in smoke concentration with brake power for various fuel blends is shown in figure 8. It is noticed that smoke emissions decrease considerably with the addition of butanol to B20. At lower loads, the smoke is higher which could be due to higher latent heat of evaporation of butanol. The higher flame temperature would give lesser smoke. The presence of oxygen in butanol enhanced the fuel combustion leading to lesser smoke emissions. At high load of 12Nm, the smoke emissions are higher for neat diesel with 3.453 FSN (Filter Smoke Number) while it is low for BU15 with 2.778 FSN.

![Figure 8. Variation in Smoke Concentration with Brake Power.](image)
3.2.4. **Carbon dioxide.** Figure 9 shows the variation in CO$_2$ emissions with brake power for various fuels. In general, higher amount of CO$_2$ in the exhaust reveals efficient combustion. It is observed that B20 possessed lesser CO$_2$ emission compared to neat diesel because of incomplete combustion. It is noticed that, with increase in addition of butanol percentage, CO$_2$ emissions are reduced to a greater extent. An average reduction of CO$_2$ emissions by 35% is achieved for butanol blends compared to B20 at load of 10 Nm.

![Figure 9. Variation in CO$_2$ with Brake Power.](image)

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Figure 10 shows the variation of cylinder pressure with crank angle at full load. The shorter ignition delay possessed by butanol-biodiesel blends helped in advancement of start of combustion which created rise in cylinder pressures greater than that of diesel and B20. This could be also due to the low auto ignition temperature and high vaporization rate of n-butanol.

![Figure 10. Variation of cylinder pressure with crank angle.](image)

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The peak cylinder pressure developed for test fuels at maximum load of 12Nm is shown in figure 11. It is observed that peak pressure is highest for BU5 at 63.769 bar which could be due to high temperatures developed and higher rate of vaporization compared to other fuels. But with 10% and
15% addition of butanol to B20, peak pressures reduced compared to BU5 which could be due to longer ignition delay. B20 possessed the lowest peak pressure. It is noticed that the peak pressure for BU5 is 4.3% and 2.8% more than that of B20 and neat diesel respectively. The peak pressure of BU15 is almost the same as that for neat diesel.

![Figure 11. Comparison of peak cylinder pressure (bar) for various fuels.](image)

### 4. Conclusion

The performance and emission characteristics of diesel engine with n-butanol-biodiesel blends are compared with that of neat diesel and B20 fuel. The following conclusions are drawn based on the experimental results.

1. BSFC is increased for the biodiesel blend compared to neat diesel and reduced with the addition of butanol to biodiesel blend B20.
2. BTE decreases for B20 compared to neat diesel and increases by an average of 15% with butanol additive.
3. HC emissions are higher for biodiesel blend B20 compared to diesel and increased when the percentage of n-butanol is increased. Among all the test fuels, diesel possessed the least emissions.
4. NOx emissions are decreased with increase in the butanol concentration. An average decrease of 18% and 23% is observed for butanol blends relative to diesel and blend B20 respectively.
5. CO\textsubscript{2} emissions are lowest for butanol blends among all the test fuels.
6. Smoke Concentration is less for B20 compared to neat diesel and reduced with the addition of butanol.

From this study, it is concluded that the use of n-butanol enhances engine performance. Emissions such as Nitrogen oxides, Carbon dioxide and Smoke concentration will be reduced with the usage of biodiesel additives.

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### Appendix

**Sample calculation for uncertainty analysis**

The possible errors in the measuring devices such as Speed indicator(dN), Stop Watch (dt), Burette (dV) and Load cell (dT) are 5 rpm, 0.01s, 0.1cc and 0.1 Nm respectively.
1. Uncertainty in brake power (BP) = \[(dN/N)^2 + (dT/T)^2\]^{0.5} = [(5/2300)^2 + (0.1/10)^2]^{0.5} = 0.01023 kW = ±1.02%

2. Uncertainty in fuel consumption (FC) = \[(dV/V)^2 + (dt/t)^2\]^{0.5} = [(0.1/10)^2 + (0.01/30.37)^2]^{0.5} = 0.010 kg/h = ±1.0%

3. Uncertainty in brake thermal efficiency (BTE) = \[(dBP/BP)^2 + (dFC/FC)^2\]^{0.5} = [(0.01023)^2 + (0.010)^2]^{0.5} = 0.01431 = ±1.43%

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