

# Performance Evaluation of a Diesel Engine Utilising Varying Ratios of Ethanol-Butanol Additives Department of Mechanical Engineering CBIT Hyderabad

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**Abstract:** This study examines how a diesel engine behaves when ethanol and butanol are mixed with regular diesel fuel in different proportions. The aim is to determine whether these cleaner, renewable fuels can partially replace diesel without compromising engine performance while reducing harmful emissions. To do this, several fuel blends were prepared and tested in a diesel engine under different load conditions and ratios (D85E7.5B7.5, D80E10B10, D75E12.5B12.5). During the experiments, important performance factors such as fuel efficiency, fuel consumption, and exhaust temperature were recorded. At the same time, emissions such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO<sub>x</sub>), and smoke levels were measured to assess the environmental friendliness of each blend. The results show that adding ethanol and butanol improves the combustion process because these fuels contain oxygen, which helps the fuel burn more completely. This leads to lower emissions of pollutants like CO, HC, and smoke, making the engine cleaner compared to using pure diesel. However, when the proportion of ethanol and butanol is increased too much, the engine may consume more fuel and show a slight drop in efficiency, mainly because these fuels have lower energy content than diesel. In some cases, higher blends can also affect how smoothly the engine runs. Overall, the study suggests that using an optimal mix of ethanol and butanol with diesel can provide a good balance between performance and emission reduction, making it a practical and eco-friendly alternative for diesel engines.

**Keywords:** Diesel engine performance, Ethanol–diesel blends, Butanol–diesel blends, Alternative fuels, Renewable fuels, Fuel blending ratio

## 1. INTRODUCTION

### Background and Global Energy Scenario

Currently, the contemporary world is experiencing a two-sided threat due to the depletion of traditional oil reservoirs and increasing environmental effects caused by the burning of fossil fuels. With an ever-increasing global energy need, transportation and agriculture, which use the most common (CI) engines, contribute significantly to GHG pollution. The accumulation of CO<sub>2</sub>, NO<sub>x</sub> and other pollutants in the atmosphere causes the warming of our planet; thus, the global community tends to move towards alternative and environmentally friendly energy sources.

### The Role of Oxygenated Fuels

In order to address such environmental concerns, research has taken an altogether new turn towards "Oxygenated Fuels" obtained through biomass. Ethanol and Butanol have become prominent contenders because they can be obtained from renewable resources. Ethanol is easily obtainable and contains a large amount of oxygen, making the fuel burn more efficiently. However, the major drawbacks of ethanol include low cetane value and poor compatibility with diesel fuels.

### The Rationale for BED (Butanol-Ethanol-Diesel) Blends

This study seeks to examine the role of Butanol as a cosolvent for bridging the difference between Ethanol and Diesel. While Ethanol has a good amount of oxygen content in the form of ethanol alcohol, Butanol has an advantage over Ethanol in terms

of energy density, low hydrophilicity, and miscibility with diesel fuel. The use of the BED blend can be helpful due to these reasons.

### Rationale for the Selection of n-Butanol

The inclusion of n-Butanol in the ternary mixture (BED) was strategically chosen to counter the inherent drawbacks associated with binary mixtures of Ethanol and Diesel. The choice was rationalised because

### Enhanced Miscibility and Phase Stability

One of the main problems associated with the use of Ethanol-Diesel blends lies in their ability to experience phase separation in the event of even slight moisture or in case of low temperatures. n-Butanol plays a major role as an efficient cosolvent and surfactant. This molecule helps in establishing a connection between polar ethanol molecules and non-polar diesel molecules.

### Improved Calorific Value and Performance

Even though ethanol contains a high amount of oxygen, the calorific value of ethanol is considerably less than that of diesel. However, n-Butanol has more energy density than ethanol, i.e., (approx 33-34 MJ/kg) for butanol, while the calorific value of ethanol is ( 26.8 MJ/kg). With the addition of butanol, the decrease in the calorific value of the mixture is reduced, ensuring BP remains high and BSFC does not rise excessively.

### Combustion Characteristics (Cetane Compatibility)

The n-butanol has a higher value of the cetane number compared to that of ethanol. It is very important for the CI engine because fuels with low values of cetane numbers create longer ignition delays as well as knocking effects. Due to this factor, butanol plays an important role in ensuring the stability of ignition delays and smooth pressure increase.

### Physical Properties and Engine Safety

In contrast with ethanol, n-Butanol is less hydrophilic (meaning it absorbs fewer water molecules from the air) and causes little corrosion damage to the internal engine parts, such as fuel injectors and rubber seals. The fact that the latent heat of

vaporisation is low ensures that the cylinder temperature is maintained at an optimum level for auto-ignition in the diesel engine.

Table-1: BED ratios

Fuel Blend	Diesel (%)	Ethanol (%)	Butanol(%)
Pure Diesel	100	0	0
BED15	85	7.5	7.5
BED 20	80	10	10
BED 25	75	12.5	12.5

## II. OBJECTIVES

### Primary Objectives:

- Investigate the effect of varying ethanol-butanol ratios on diesel engine performance
- Determine optimal additive ratio for maximum thermal efficiency and minimum emissions
- Analyse combustion characteristics across different engine operating conditions

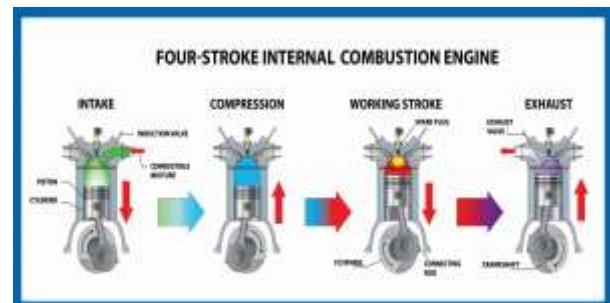
**Secondary Objectives:** → Compare performance with pure diesel baseline

- Study the influence of engine load on efficiency
- Evaluate environmental impact through emissions analysis
- Develop recommendations for practical implementation

**Experimental Scope:** • Test conditions: Varying engine speeds and loads

- **Fuel blends:** Multiple ethanol-butanol ratios (7.5%,10%,12.5%)

Comprehensive data collection and statistical analysis



### III. LITERATURE REVIEW

Ranjan & Kumari (2024) studied the ethanol blending program in India and its significance in terms of energy sustainability. According to their research, government policies aimed at implementing ethanol blending up to 20% by 2025 had multiple benefits, such as minimising the import of crude oil, reducing greenhouse gases, and promoting rural development by boosting ethanol consumption. The authors pointed out the significance of using ethanol, which is a renewable biofuel produced from sugarcane and other sources.

Moreover, they identified several major problems associated with the ethanol blending program in India. First, there was insufficient capacity for producing ethanol. Second, there was a lack of raw materials required for producing ethanol. Finally, there were various logistical problems connected with blending and distribution.

"Ethanol Blending of Petrol in India – APR" was an article on the impact of using ethanol and petrol blends in engines with internal combustion. According to the research, ethanol blends contribute to better combustion properties owing to the oxygen contained within ethanol, thus increasing engine efficiency and minimising the emission of carbon monoxide and unburnt hydrocarbons. Moreover, the research showed that ethanol blends have higher octane numbers, ensuring smooth engine performance.

Another advantage mentioned in the paper is the fact that ethanol fuel blends are eco-friendly and contribute to reducing the country's dependency on fossil fuels since ethanol is a renewable fuel source that can be easily decomposed in the environment. Despite the above-mentioned benefits, the researchers discussed various problems related to storage stability, mixing uniformity, and necessary infrastructure. As a result, the article proved that ethanol blending was a reasonable solution for India.

From the literature on the role and effects of conventional alcohol additives, it is established that there are five candidates under consideration for sustainable energy sources in place of fossil

fuels as CI engine fuel. They include methanol, ethanol, propanol, butanol, and pentanol. These alcohols have shown that their addition to the percentage of oxygen is capable of improving the quality of combustion and reducing the emission of pollutants. For example, methanol enhances flame propagation and lowers. Due to its extinguishing effect, which is associated with its high latent heat value. On the contrary, blends containing ethanol result in CO and HC emissions due to its extremely cooling effect. However, when considering the effects of high alcohol additives in relation to unmodified fuels, propanol, butanol, and pentanol are more effective than . It has been found that these alcohol additives provide great importance in managing pollution, but need to be used in specific dosages.

An experiment done on the performance and emission levels of a high-speed direct injection diesel engine concluded that n-butanol can be an efficient biofuel for use in high blend ratios. The experiment involved the use of butanol diesel blends with a highest percentage composition of Bu40, which resulted in an increase in pressure during combustion while improving the rate of burning without interfering with the maximum values of engine power and torque. Though butanol blended fuels slightly increase BSFC, they significantly improve BTE over diesel fuel. Emission levels showed that smoke levels were highly reduced by the presence of butanol. The effect on other pollutants was largely dependent on load; low loads had reduced levels of and high levels of CO emissions, while at high loads, there were high levels of but low CO emission levels. This indicates that Bu40 blends can be employed in passenger car diesel engines effectively.

### IV. METHODOLOGY

#### Fuel Preparation and Blending

The critical part of this experiment is the preparation of the fuel. To ensure the accuracy of the fuel ratios, the process of blending was conducted using precise volumetric glassware. With the splash blending technique, we have monitored the ratios for 24 hours so that we could confirm that the fuel has blended thoroughly with the help of n-Butanol. As table-1 shows, the

ratios of the BED fuel. Precautions were taken to maintain the fuel in a controlled environment.

### Experimental Setup



The engine was coupled to an Eddy Current Dynamometer to apply a variable load during the experimental trials. The dynamometer works by generating electromagnetic fields that create braking torque on the engine's output shaft, allowing for precise control over the engine speed and load.

In this experiment, to obtain data for the required parameters, a systematic procedure was followed so that results were obtained. Here, sensors, instruments, and electrical devices are used. The following instruments were employed:

**Burette and Stopwatch:** These two instruments were used for calculating fuel flow. Fuel is poured into the container, and it is connected to the burette, then it is connected to the intake valve of the engine. As the fuel enters the burette, the stopwatch is taken then 10 observations are taken on the burette. This procedure shows how fast the fuel is consumed.

**Eddy Current Dynamometer:** The dynamometer is used to apply a load on the engine. With the help of a dynamometer, load can be applied, and the variations of the load can be adjusted according to the individual.

**AVL Smoke Meter and Exhaust Analyser:** This instrument detects the smoke, and it analyses the gas composition in the exhaust. While the engine is working, the exhaust gases are produced. These gases are checked with a smoke meter, and then it is analyzed to check the composition of the gases, like

### Test Procedures and Parameters

- **Fuel Preparation**

The preliminary stage involved the preparation of fuel. There are three ratios made with diesel, ethanol, and butanol. Diesel and ethanol were blended with the help of butanol. As diesel and ethanol do not blend with each other, butanol is used to blend them together. The boiling point of butanol is lower than that of base diesel, and its volatility is greater. As the fuel is being injected into the combustion chamber, where it is extremely hot, the butanol portion will reach its boiling point quickly. The droplet's inner pressure will increase, causing it to break down into smaller droplets. After the blending of the fuels, the fuels are kept aside. The reason for keeping the fuels aside is to ensure that ethanol and diesel are blended thoroughly. Even though butanol is blended with them, the fuels should be monitored, as there may be chances of diesel and ethanol not blending thoroughly.

- **Engine Preparation**

The ternary fuel which are made is not to be used immediately. As the engines are made for diesel as the fuel, the new fuel cannot be used in the engine. If it is used, then it will damage the engine. To ensure the accuracy of the performance data, the engine was initially operated on neat diesel until it reached steady-state thermal conditions. Transitioning directly to the ternary BED blends without this baseline stabilisation would lead to inconsistent results.

- **Applying Load**

After running the engine with diesel for sometime one of the ternary fuels is taken. We have made three different ratios of fuel. In Table 1, the information on the three different fuels is given. We have taken the fuel respectively and performed performance parameters on the engine. With the help of a dynamometer, we

have applied loads on the engine to get the desired results. The loads on which the fuel was tested are 0, 25%, 50%, 75%, 100%. The fuel was tested on respective loads and constant speeds. The speed was kept constant throughout the experiment so that it would not disturb the experiment.

- Data Collection

For each load and for each fuel blend, the following parameters were recorded:

1. Brake Power(BP)
2. Fuel Consumption
3. Brake Specific Fuel Consumption(BSFC)
4. Brake Thermal Efficiency(BTE)
5. Mass of Air Consumed
6. Air Fuel Ratio
7. Volumetric Efficiency
8. Brake Mean Effective Pressure

### Mathematical Calculations

To show the mathematical calculation performed for the experiment, an example is taken. From Table 1, the BED 15 fuel calculations are taken. The following are the calculations for the performance parameters:

#### Calculation of the Brake Power

Brake Power is the actual power delivered by the engine at the output shaft or crankshaft, available for useful work. It is calculated as the total power generated in the engine cylinders minus the power lost to internal friction and pumping.

$$BP = \frac{V * I}{1000 * \eta_d}$$

BP = Brake Power (kW)

V=Voltmeter (230V)

I = Ammeter in amperes (0,3,6,9,12)

= Efficiency of dynamometer = 0.85

#### Fuel Consumption

Fuel Consumption is the total mass of fuel consumed by the engine per unit of time. It quantifies the rate at which chemical

energy is supplied to the engine to maintain a specific operating condition or load.

$$mf = \left(\frac{10}{t}\right) * (pd) * \left(\frac{3600}{1000}\right)$$

mf= mass of fuel in kg/h

t= Time taken for collecting 10cc of fuel in seconds

pd= Density of Fuel in gm/cc

#### Calculation of the Brake Specific Fuel Consumption

Brake Specific Fuel Consumption is the mass of fuel consumed per unit of time for every unit of brake power produced. It serves as a standard metric to compare the fuel efficiency of different engines or different fuel blends regardless of engine size.

$$BSFC = \frac{mf}{BP} \text{ kg/kW - h}$$

#### Calculation of the Brake Thermal Efficiency

Brake Thermal Efficiency is the ratio of the energy equivalent of the brake power to the total chemical energy released by the combustion of the fuel. It indicates the degree of effectiveness with which the engine converts the heat energy of the fuel into useful mechanical work.

$$BTE = \frac{BP * 1000}{mf * CV_d}$$

= Calorific Value of BED = 39,459kJ/kg

#### Mass of Air Consumed

Mass of Air Consumed is the actual mass of intake air that enters the engine cylinders over a specific period. It is a fundamental parameter used to determine the efficiency of the induction process and the completeness of the combustion reaction.

$$ma = Cd * a * \sqrt{2 * 10 * g * h * \rho_a * 3600}$$

ma = Mass of air induced in the engine in kg/h

a = Area of the orifice in square meters =  $\frac{\pi * d^2}{4}$

= diameter of orifice = 0.02m

= 0.000311

h = Difference of water column (h1-h2)

$$\rho_a = \left(\frac{Pa}{750}\right) * 10^5 * \frac{1}{R * Ta}$$

Pa = Atmosphere pressure of mercury (750)  
R = Gas constant for air = 287 J/kg-K  
Ta = Room temperature in Kelvin = 309 Kelvin

### Air Fuel Ratio

The Air-Fuel Ratio is the ratio of the mass of air drawn into the cylinder to the mass of fuel injected. It defines the mixture strength and determines the chemical environment within the combustion chamber, influencing both performance and exhaust emissions.

$$A:F = \frac{ma}{mf}$$

### Volumetric Efficiency

Volumetric Efficiency is the ratio of the actual mass of air drawn into the cylinder during the intake stroke to the theoretical mass of air that would occupy the cylinder's displaced volume at ambient temperature and pressure. It measures the effectiveness of the engine's "breathing" system.

### Brake Mean Effective Pressure

Brake Mean Effective Pressure is a theoretical constant pressure which, if exerted on the piston for the entirety of the power stroke, would produce the same amount of brake power as is actually measured. It is used to compare the performance and torque-producing capacity of engines independent of their displacement. improved thermal efficiency than pure diesel, mainly because ethanol and butanol are oxygenated and allow better burning inside the cylinder. Low viscosity in ternary blends leads to better atomization of the fuel.

## V. EXPERIMENTAL PARAMETERS

### Engine Specifications:

- Type: Single-cylinder, four-stroke diesel engine
- Cylinder arrangement: Vertical
- Core: Bore:80mm, stroke:110mm
- Dynamometer Spec: Frame: 180, Voltage: 230V, Max current: 12 amperes
- Fuel Injection System: Direct injection

### Operating Conditions:

- Engine Speed: 1500RPM (variable)
- Load Conditions: 0%, 25%, 50%, 75%, 100% load
- Steady-state operation: 5 minutes per condition

### Fuel Blend Specifications:

- D100 (Baseline - Pure Diesel)
- D85E7.5B7.5 (85%-850ml Diesel + 7.5%-75ml Ethanol + 7.5%-75ml Butanol)
- D80E10B10 (80%-800ml Diesel + 10%-100ml Ethanol + 10%-100ml Butanol)
- D75E12.5B12.5 (75% -750ml Diesel + 12.5%-125ml Ethanol + 12.5% -125ml Butanol)



## VI. RESULT AND ANALYSIS 6.1 PERFORMANCE ANALYSIS

Brake Power

$$1. [I=0] \frac{230 \times 0}{1000 \times 0.85} = 0 \text{ kW}$$

$$2. [I=3] \frac{230 \times 3}{1000 \times 0.85} = 0.8117 \text{ kW}$$

$$3. [I=6] \frac{230 \times 6}{1000 \times 0.85} = 1.623 \text{ kW}$$



$$4. [I=9] \frac{230 \cdot 9}{1000 \cdot 0.85} = 2.43 \text{ kW}$$

$$5. [I=12] \frac{230 \cdot 12}{1000 \cdot 0.85} = 3.24 \text{ kW}$$

**Fuel Consumption**

$$mf = \left(\frac{10}{t}\right) \cdot (\rho d) \cdot \left(\frac{3600}{1000}\right)$$

- 1) [I=0] T = 54sec =  $\frac{10 \cdot 0.80 \cdot 3.6}{54} = 0.533$
- 2) [I=3] T = 41sec = 0.694
- [I=9] T = 29sec = 0.966
- 3) [I=6] T = 34sec = 0.835
- 4) [I=12] T = 23sec = 1.252

**Calculation of the brake specific fuel Consumption (BSFC)**

$$BSFC = \frac{mf}{BP} \text{ ---kg/kW-h}$$

- 1) [I=3] =  $\frac{0.694}{0.812} = 0.855 \text{ kg|kW-h}$
- 2) [I=6] = 0.514 kg/kW-h
- [I=12] = 0.386 kg/kW-h
- 3 [I=9] = 0.397 kg/kW-h

**Calculation of the brake thermal efficiency (BTE)**

$$BTE = \frac{BP \cdot 3600}{mf \cdot CVd}$$

- 1) [I=3] =  $\frac{0.812 \cdot 3600}{0.694 \cdot 39459} = 0.106$
- 2) [I=6] = 0.177
- 3) [I=9] = 0.229
- 4) [I=12] = 0.236

**Mass of air consumed**

$$ma = Cd \cdot a \cdot \sqrt{2 \cdot 10^6 \cdot g \cdot h \cdot \rho a \cdot 3600}$$

$$= 0.62 \cdot 0.00031 \cdot \sqrt{2 \cdot 10^6 \cdot 9.81 \cdot 3.5 \cdot 1.127 \cdot 3600}$$

$$ma = 6.10 \text{ kg}$$

**Air - fuel ratio**

- Air fuel ratio, A: F =  $\frac{ma}{mf}$
- 1) [I=0] = 11.44
  - 2) [I=3] = 8.9
  - 3) [I=6] = 7.3
  - 4) [I=9] = 6.31

$$5) [I=12] = 4.87$$

**Volumetric efficiency** ( $\eta_v$ )  $\eta_v = \left(\frac{ma}{60}\right) \cdot \left(\frac{1}{\rho a}\right) \cdot \left(\frac{2}{N}\right) \cdot \left(\frac{1}{v_s}\right) \cdot 100$

$$= \left(\frac{6.10}{60}\right) \cdot \left(\frac{1}{1.127}\right) \cdot \left(\frac{2}{1500}\right) \cdot \left(\frac{1}{0.0005526}\right)$$

$$= 0.329 \cdot 0.887 \cdot \frac{1}{750} \cdot \frac{1}{0.0005526}$$

$$= 21\%$$

**Brake Mean Effective Pressure**

$$BP = \frac{P \cdot 10^5 \cdot A \cdot I \cdot \left(\frac{n}{60}\right) \cdot K}{1000 \cdot BP \cdot 1000 \cdot 60}$$

$$= \frac{10^5 \cdot A \cdot L \cdot n \cdot K}{1000 \cdot BP \cdot 1000 \cdot 60}$$

- 1) [I=0] = 19.04
- 2) [I=3] = 19.04
- 3) [I=6] = 37.95
- 4) [I=9] = 56.94
- 5) [I=12] = 75.93

**Emission Analysis**

**Fuel 1 –(BED blend)- D85E7.5B7.5 (85%-850ml Diesel + 7.5%-75ml Ethanol + 7.5%-75ml Butanol)**

- > O<sub>2</sub> = 19%
- > PEF = 0.530
- > Analyse = 96.2
- > Smoke = 0% = 29-30%
- 100% = 79-84%

**Fuel 2 –(BED blend)- D80E10B10 (80%-800ml Diesel + 10%-100ml Ethanol + 10%-100ml Butanol)**

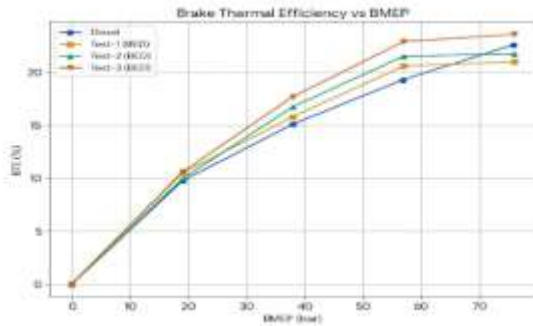
- > O<sub>2</sub> = 19%
- > PEF = 0.530
- > Analyse = 96.8
- > Smoke = 0% = 31-33%
- 100% = 85-88%

**Fuel 3 –(BED blend)- D75E12.5B12.5 (75%-750ml Diesel + 12.5%-125ml Ethanol + 12.5%-125ml Butanol)**

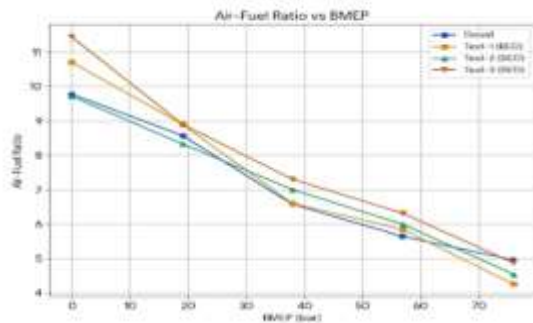
- > O<sub>2</sub> = 19%
- > PEF = 0.530
- > Analyse = 97.7
- > Smoke = 0% = 31-36%
- 100% = 86-91%

## VII. GRAPH AND TABLE ANALYSIS.

### Graph

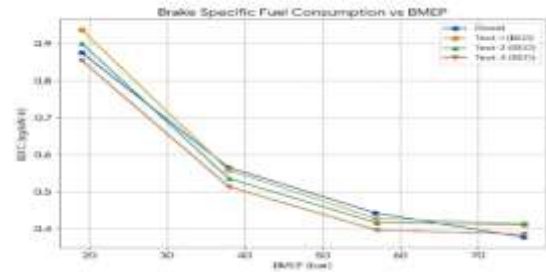


As Brake Mean Effective Pressure (BMEP) increases, BTE increases for all fuels. Test-3 (BED) consistently shows the highest efficiency among all blends, even surpassing pure Diesel at most load points. Higher BTE indicates better conversion of chemical energy in the fuel into useful mechanical work. AFR decreases as BMEP increases because more fuel is injected to handle higher loads.



Test-3 starts with a significantly leaner mixture at low loads compared to Diesel, but converges at full load. The higher initial AFR for BED blends suggests better oxygen availability (likely due to the oxygenated nature of ethanol/butanol), which promotes more complete combustion.

BSFC drops sharply as the load (BMEP) increases. Test-3 (BED) maintains the lowest BSFC curve throughout the mid-to-high load range. BSFC is the inverse of efficiency. Lower values mean the engine consumes less fuel to produce the same amount of power, proving the economic and technical viability of the BED blend.



### Table analysis

Fuel 1 (Table)- D85E7.5B7.5 (85%-850ml Diesel + 7.5%-75ml Ethanol +7.5%-75ml Butanol)

Sn	Load		BP	mf	BSFC	CV	BTE	Ma	Air fuel	vol	BMEP
	A	%									
1	0	0	0	0.570	0	0	0	6.30	9.7	21	0
2	3	25	0.8117	0.68	0.837	0.105	6.10	8.9	21	19.04	
3	6	50	1.035	0.915	0.559	0.158	6.30	6.6	21	37.9	
4	9	75	2.435	1.041	0.428	0.206	6.30	5.84	21	56.4	
5	12	100	3.247	1.429	0.414	0.210	6.30	4.26	21	75.9	

TEST 2 (Table)- D80E10B10(80%-800ml Diesel + 10%-100ml Ethanol + 10%-100ml Butanol)

Sn	Load		BP	mf	BSFC	CV	BTE	Ma	Air fuel	vol	BMEP
	A	%									
1	0	0	0	0.628	0	0	0	6.10	9.71	21	0
2	3	25	0.8117	0.732	0.901	0.0997	6.10	8.33	21	19.04	
3	6	50	1.035	0.871	0.536	0.1675	6.10	7	21	37.9	
4	9	75	2.435	1.017	0.417	0.215	6.10	5.98	21	56.4	
5	12	100	3.247	1.341	0.409	0.219	6.10	4.54	21	75.9	

## VIII. FUTURE SCOPE

### Optimisation of Fuel Blend Ratios Using AI/ML Techniques

Futuristic research can apply artificial intelligence techniques such as ANN and genetic algorithms to determine the optimal blend ratio of ethanol, butanol, and diesel depending on different operating parameters of the engine.

### Engine Modification and Injection Parameter Study

This study employs an unmodified standard diesel engine. Future research may investigate:

Different times and pressures for injection.

Different ways to inject.

EGR (exhaust gas recirculation) and turbocharging.

These changes might make combustion more efficient and lower emissions even more.

### Multi-Cylinder and Real -World Engine Testing

This study is confined to a single-cylinder engine; subsequent research should corroborate findings on multi-cylinder engines and commercial vehicles to assess real-world relevance and scalability.

### Cold Start and Transient Condition Analysis

Because of their high latent heat of vaporisation, alcohol blends usually make cold starts harder. Future research should examine: Emissions when the engine is cold.

Changing engine behaviour (speeding up and slowing down).

How well it works in different weather conditions.

### Advanced Combustion and CFD Analysis

You can use Computational Fluid Dynamics (CFD) simulations to look at:

How combustion works in the cylinder.

The spray properties of mixed fuels.

Rate of heat release and flame spread

This will give us more information than what we can get from experiments.

### Exploration of Higher Blend Ratios and Alternative Alcohols

Further research can go on to explore blends above 12.5%, as well as:

Methanol, pentanol, or bio-butanol variants.

Bio-blow fuels blended with biodiesel

## IX. CONSTRAINTS & LIMITATIONS

### Technical Limitations:

- Single-cylinder engine (limited scalability to multi-cylinder)
- Fixed injection timing (variable timing not feasible)
- Limited test speed range due to engine specifications
- Emissions analyzer accuracy  $\pm 2-5\%$  depending on parameter

### Resource Constraints:

- Laboratory facility availability and booking
- Instrumentation accuracy and calibration costs
- Fuel blend preparation time • Budget limitations for extended testing

### Operational Challenges:

- Weather conditions affecting engine cooling
- Instrument drift during extended testing
- Variations in fuel properties across batches
- Safety regulations and emission standards compliance

### Mitigation Strategies:

- Multiple test repetitions for data consistency
- Careful instrumentation maintenance
- Controlled laboratory environment
- Adherence to all safety protocols



## X. CONCLUSIONS

The experimental investigation reveals that the Test-3 (BED) tri-fuel blend exhibits superior performance characteristics compared to conventional Diesel. It achieved the highest Brake Thermal Efficiency (BTE) and the lowest Brake Specific Fuel Consumption (BSFC), particularly under medium to high load conditions.

10.2 The lower BSFC and higher BTE of the Test-3 blend indicate improved combustion quality. This is supported by the Air-Fuel Ratio data, which suggests that the oxygenated components in the BED blend facilitate a leaner and more efficient burn than pure Diesel.

10.3 The inclusion of n-butanol as a cosolvent successfully addressed the solubility issues typically associated with ethanol-

diesel blends, resulting in a stable fuel that performs better than standard diesel under high-load conditions.

10.4 The leaner combustion (higher AFR) and improved thermal efficiency (higher BTE) observed with Test-3 suggest a potential reduction in soot and carbonaceous emissions, making these BED blends a viable "drop-in" green technology for existing diesel engines.



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