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Diesel Ethanol Blends in Genset Engine: Ensuring Diesel-Like Performance at Reduced Emissions Using Optimal Cetane Enhancer-Based Additive Composition

Shailesh Sonawane[1,2], Ravi Sekhar[1*], Arundhati Warke[1], Sukrut Thipse[2], Sandeep Rairikar[2], Prasanna Sutar[2], Debjyoti Bandyopadhyay[2], Ajinkya Jadhav[2]

[1] Symbiosis Institute of Technology (SIT), Pune Campus, Symbiosis International (Deemed University), Pune 412115, India
[2] Automotive Research Association of India (ARAI), Pune 411038, India

Corresponding Author Email: ravi.sekhar@sitpune.edu.in

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ABSTRACT

A reliable power supply forms the basis of the robust economic growth of a country. The unreliable power supply is one of the key factors driving the demand for generator sets (gensets) across India. Emissions from diesel gensets adversely affect the environment and human health. Alcohol-blended diesel can be used in gensets to reduce harmful emissions. This paper presents an investigation of the effect of additive compositions in diesel ethanol blends on the emission characteristics of a multi-cylinder genset engine. In this study, four distinct diesel ethanol blends were prepared with varying additive compositions. All blends included diesel, ethanol, and additive in a constant proportion of 90.3:7.7:2. The additive was composed of three constituents: 2-Ethyl Hexanol, 2-Ethyl Hexyl Nitrate, and Ethomeen. These constituents were mixed in varying proportions (1:0.20:1, 1: 0.21:1, 1: 0.23:1, and 1:0.24:1 by weight) to create four distinct fuel blends, ED1, ED2, ED3 and ED4, respectively. Subsequently, mass emission tests (CO, HC, NO_x, PM, and smoke) were conducted on a genset engine using these blends. Primary results indicate that the ethanol blended diesel fuels generate lower emissions when compared to base diesel, and the blends ED1 and ED3 achieved the best emission characteristics. The NO_x, CO, and PM emissions were reduced by 30%, 9%, and 20%, respectively, while HC emissions increased by approximately 25% with the ED blend compared to diesel. It can be concluded that existing genset engines can easily adapt to ED7.7 without significant modifications to their current hardware, such as the piston bowl, compression ratio, or fuel system. The compatibility of ED7.7 with these in-use genset engines lowers the cost and complexity of transitioning to cleaner fuel alternatives, making it a practical solution for widespread adoption.

1. INTRODUCTION

One of the most significant aspects of economic growth is power supply. Power is essential for nationwide economic prosperity. For the Indian economy to grow steadily, suitable infrastructure must be developed continuously. India's economy is expanding quickly, and it requires energy to achieve its growth goals in a sustainable way. The Government of India (GOI) emphasis on "power for all" has helped accelerate the production of energy. The power sector comprising of generator sets plays an important role in meeting the country's power requirements. The unreliability of the electricity grid is a key factor driving this industry. India's electricity grids are not built to endure extreme weather conditions, earthquakes, or fire, which cause power interruptions. Increased generator set adaption across industries is due to the need for uninterrupted power supply.

Currently, the most widely implemented generator sets in India are diesel-powered. Humans, as well as the environment, are harmed by the emissions of these diesel generator sets. These gensets release harmful gases, which include nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons (HC), sulfur oxides (SO_x), particulate matter (PM), volatile organic compounds (VOC), and carbon dioxide (CO_2) [1, 2]. These gases pose a serious risk to human health.

The increased use of generator sets is also supported by inconsistent power delivery at disparate regions. The installed capacity of diesel generators caters to more than 90% of the backup power requirement in India [3]. Diesel generators' contribution to India's air pollution problem. According to the Centre for Science and Environment (CSE), diesel generators contribute a significant chunk – between 7% and 18% – of air pollution in cities that haven't met the National Ambient Air Quality Standards for over 5 years. Diesel generators are significant contributors to air pollution due to toxic combustion chemicals, including NO_x, CO, PM, and HC. Diesel generators usually emit 120-220 mg/m³ of $PM_{2.5}$ [4]. These pollutants are extremely harmful and lead to respiratory diseases, cardiovascular problems, and even premature death. The Central Pollution Control Board (CPCB) reports that diesel generators contribute about 15% to the urban air pollution in industrial areas [5]. The environmental impact is also a cause of concern, as diesel burning releases huge amounts of CO_2, adding to global warming. Diesel pollutants can aggravate asthma, bronchitis, emphysema, and weaken the heart. Longer exposure to this pollutant may lead to cancer. In an effort to contain the challenges posed by noise and air pollution, regulatory authorities have prescribed the need to reduce emissions by significant numbers for the existing gensets [6].

CPCB and the National Green Tribunal (NGT) have established specific standards for controlling harmful gas emissions and the resultant environmental contamination. NGT has ordered that in-use generator sets can be used only if their PM emissions are reduced by 73% or more. In this way, stricter diesel engine requirements have been established to reduce NO_x, particulate matter, and CO_2 emissions, apart from fuel consumption. Despite these laws, a lack of scalable and cost-effective alternatives impedes the move away from diesel generators and the actual need for cleaner technology and biofuel-based solutions.

One of the ways to mitigate this issue is the usage of alternate fuels. The best options are biofuels such as ethanol and biodiesel because they behave in an environmentally benign manner and share many practical characteristics with conventional diesel fuel. Bioethanol is one of the most significant biofuels due to its positive environmental impact [7]. Renewable energy obtained from biological sources is indigenous, less polluting, and virtually inexhaustible. Moreover, a country like India is endowed with abundant renewable energy sources. It has been fifty years since oxygenates were first used as fuel additives to assist cleaner combustion of petroleum fuels. Numerous researchers have examined the effects of combining various oxygenates with gasoline fuel. Alcohols like ethanol and methanol can be added to gasoline due to their benefits, such as a higher-octane number and lower hydrocarbon and carbon monoxide emissions. Due to the various advantages of blending ethanol with gasoline, this particular blended fuel finds widespread application in engines, and hence, a lot of research has been carried out in this field.

On the other hand, researchers have faced difficulties in blending ethanol with diesel. Contrary to gasoline, diesel and ethanol are difficult to mix, and particular ingredients are needed to increase the lubricity, blending and cetane number of the diesel-ethanol blends. Ethanol has low solubility in diesel fuel. Water tolerance and phase separation are critical issues in diesel-ethanol blended fuels. Moreover, ethanol possesses a low cetane number, while a higher cetane number is desired for diesel engines for easy ignition and minimal delay. Because ethanol has a substantially lower dynamic viscosity than diesel fuel, lubricity may be an issue with ethanol-diesel blended fuel. Blending diesel with ethanol is usually limited to anhydrous ethanol because of its low solubility in diesel. The solubility of the diesel-ethanol mixture varies based on the hydrocarbon composition of the diesel fuel, its wax content, and the surrounding temperature. The solubility of mixed fuels varies based on their water content. The solubilizer added in Ethanol-diesel blends prevented the phase separation, which is critical [8]. Emulsifying additives further improved the qualities of diesel and ethanol blends by preventing the formation of two separate phases [9]. Various additives such as isopropanol, oleic acid, and ethylene acetate were also used to form the homogeneous mixture. Further 1% diethyl ether (DEE) was added to improve the cetane number of the diesel ethanol blend [10]. Also, ditert-butyl peroxide (DTBP) and 2-ethylhexyl nitrate (2-EHN) were used to enhance the cetane number by some of the researchers and found suitable as the engine performance was improved [11]. Diesel engines can employ a blend of ethanol to cut emissions and encourage the use of greener fuels.

There are various key challenges to using diesel-ethanol blends, which are briefed below:

- The lubricity of ethanol is very poor, and thus, lubricious additives are required in neat ethanol [12]. Otherwise, fuel system components like fuel pumps and injectors may face wear issues.
- There is a risk to engine durability with diesel-ethanol blends because diesel and ethanol are immiscible. Hence, a suitable additive is required to ensure engine durability by addressing this issue.
- The addition of ethanol to diesel decreases the cetane number of the overall blend, further deteriorating the combustion process. This suggests the need for a cetane improver.
- The higher latent heat of vaporization of ethanol causes diesel-ethanol blended engines to have cold starting problems.
- Ethanol is hygroscopic in nature which means it has great affinity towards water. So, water tolerance of the blend needs to be improved for better performance.
- Heat losses in the cylinder decrease as a result of ethanol's lower flame temperature than diesel.

There are several other issues when considering the preparation of diesel-ethanol blends, which can be overcome by judicious choice of suitable additives.

Considering the changes in the fuel properties such as calorific value, laminar flame speed, and cetane number, the use of a diesel-ethanol blend as a replacement for diesel is only possible with suitable additives. In general, thorough investigations are needed to evaluate the use of alcohol-diesel blends in diesel engines, although they suffer drawbacks such as limited lubricity, a complex vaporization process, and a high auto-ignition temperature. Along with this, an important investigation gap that hasn't been filled thoroughly is the formation of diesel-ethanol mixes for multi-cylinder genset engines with varying additive concentrations. This study aims to fill this research gap and investigates some additive compositions in diesel-ethanol blends to improve emissions from an in-use multi-cylinder genset engine. The following section presents a brief literature review on this subject.

2. LITERATURE REVIEW

The dynamics of diesel-ethanol blend fuels have been widely studied, focusing on their emissions and performance, along with the effects of various additives. Various sub-sections have been made to understand the effect of the diesel-ethanol blend on engine performance, emission, and different additives used.

2.1 Engine emission

Pidol et al. [13] investigated ethanol-blend fuels and their combustion characteristics, such as Low-Temperature Combustion (LTC). This study shows ethanol blends' capability to reduce smoke emissions but does not cover their effect on PM and the whole spectrum of regulated emissions over a wide range of blend levels

Kannan [14] investigated the effects of injection timings and pressures on a single-cylinder diesel engine using diesel-biodiesel-ethanol blends. In the case of higher injection pressures, such as 240 bar, it resulted in a smoke emission reduction of up to 40.3% due to the better availability of oxygen from ethanol and biodiesel. The emissions of CO, CO_2, NO_x, and smoke were found to be lower than those with neat diesel. Although the above study throws sufficient light on the impact of engine tuning, no discussion has been made on how specific additive combinations will help realize similar benefits without much engine tuning. de Carvalho et al. [15] studied the addition of diethyl ether (DEE) as an auxiliary oxygenate. NO_x and PM emissions were effectively reduced at medium and high loads, where B20E + DEE blends showed higher values than pure B20 and D100 fuel. Tutak et al. [16] also investigated the co-combustion of hydrated ethanol blended diesel and biodiesel fuels, showing higher NO_x and THC emissions at increased ethanol blend fractions. These results thus reveal the trade-off between benefits and detriments among emissions as ethanol concentration changes, pointing to the importance of an optimized additive formulation in order to be able to balance such effects. Di et al. [17] focused on the particulate emissions of diesel-ethanol and biodiesel blends. For smoke opacity, higher oxygen content in, reduced aromatic compounds, and fewer C-C bonds in the fuel resulted in lower smoke opacity. Wang and Li [18] investigated how varying proportions of ethanol affect diesel engine combustion and emission characteristics. The study focused on several factors, including power output, brake thermal efficiency, brake-specific fuel consumption, and cylinder temperature and pressure. It was found that carbon monoxide (CO) and soot emissions decreased, while nitrogen oxide (NO_x) emissions increased as ethanol content rose. Wei et al. [19] studied and compared the effects of biodiesel-ethanol blends containing 5%, 10%, and 15% ethanol on combustion, performance, and emissions in direct injection diesel engines. They found that as the ethanol content increased, carbon monoxide (CO) and hydrocarbon (HC) emissions rose, while nitrogen oxides (NO_x) emissions decreased.

2.2 Engine performance

The study of Pidol et al. [13] found that the 20% ethanol blend increases engine power at full load. In the study of Kannan [14], no significant deviation in engine power was observed with various fuel blends. Wang and Li [18] investigated the impact of different ethanol proportions on the combustion and emission characteristics of diesel engines. Their study examined factors such as power, brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), as well as cylinder temperature and pressure. They found that both cylinder temperature and pressure increased with higher ethanol content. In the study of Wei et al. [19], there is drop in the power as the ethanol content got increased.

2.3 Additive

Lü et al. [8] conducted an experimental study on engine pollutant emissions and combustion characteristics of a diesel engine using a blend of ethanol and diesel fuel, along with various additives. They used a solubilizer (1.5% v/v) to form an ethanol diesel blend. Additionally, cetane number improver was (0.2%) was used to enhance the combustion process. Klajn et al. [9] tested portable engine with diesel-ethanol blend. Biodiesel composed of 70% soybean oil, 28% bovine fat, and 2% pork fat was used as an additive. As biodiesel has a higher cetane number, calorific value, flash point higher than ethanol, the addition of bio-diesel enhances the diesel-ethanol fuel properties. Shanmugam et al. [10] conducted a study on a compression ignition (CI) engine to assess its performance with a blend of diesel and high-oxygenated additives, including ethanol. Various additives were mixed with the diesel-ethanol blend to achieve a homogeneous mixture. A stability test was performed to ensure that the blend maintained its homogeneity over time. The additives tested included isopropanol, oleic acid, and ethylene acetate. The results of the stability tests indicated that oleic acid was the most effective additive, producing a better homogeneous mixture of ethanol and diesel. Specifically, 1% oleic acid was used as the additive in the ethanol-diesel blend.

Guo et al. [11] conducted a comprehensive study aimed at enhancing both the ignition properties and combustion characteristics of a blended fuel consisting of ethanol and diesel. In their research, they selected two specific cetane improvers: 2-Ethylhexyl nitrate (2-EHN) and ditert-butyl peroxide (DTBP). These additives were chosen for their potential to boost the performance and efficiency of the ethanol-diesel mixture during combustion, thus providing insights into optimizing alternative fuel formulations.

2.4 Literature gaps

Despite these developments, several gaps still exist. Most of the literature places greater emphasis on either emissions or performance without considering the interaction of tailored additive composition synergies. Furthermore, most researchers work with single-cylinder engines. Diesel-ethanol blend performance on multi-cylinder genset engines under standard test cycles has been highly neglected. Moreover, how additive stability, phase separation, and lubricity enhancement play their roles regarding long-term engine durability under real-world operation remains an open area of research.

This study aimed to address these gaps by evaluating varying compositions of diesel-ethanol blends in a multi-cylinder genset engine. The research investigates emissions and performance characteristics holistically by focusing on ED7.7 previously identified as the optimal ethanol-diesel ratio [20] and systematically varying additive formulations. The inclusion of a consistent baseline is ED7.7, which will enable an in-depth additive effect analysis while gaining some realistic impressions of blend stability, engine compatibility, and optimization of emissions.

3. METHODOLOGY

This study focused on the evaluation of varying additive compositions in diesel ethanol blends in terms of engine performance characteristics. The process of evaluating the selected diesel-ethanol blends was divided into three different stages.

This process started with the preparation of the different diesel-ethanol blends. In this particular stage various diesel-ethanol blends with different additive compositions were prepared. In the second stage, each blend was thoroughly tested as per standard test procedures under the same boundary conditions. In the third stage, the effect of change of fuel properties due to varying additive compositions were recorded in terms of engine performance metrics. Finally, detailed analyses of the best two performing blends were carried out in comparison with base diesel fuel. Figure 1 shows the process flow for the above-mentioned methodology.

Figure 1. Blend evaluation methodology

3.1 Preparation of blends

In this study, various diesel ethanol blends (ED1, ED2, ED3 and ED4) were prepared with different additive compositions. In each of these blends, diesel, ethanol, and additive were kept in the constant proportion of 90.3:7.7:2. The additive was prepared by considering properties such as phase separation, cetane number, lubricity and corrosivity. The additive was composed of three different constituents as shown in Figure 2.

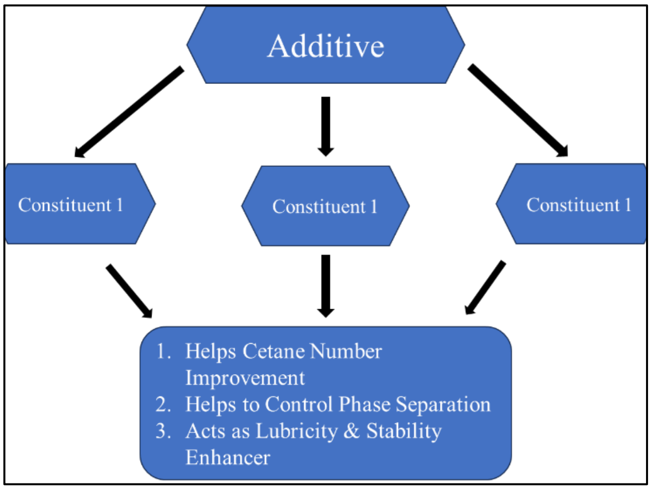

Figure 2. Additive constituents

2-Ethyl Hexanol, 2-Ethyl Hexyl Nitrate, and Ethomeen were the additive components selected in this work because they could address most of the major issues such as phase separation, loss of cetane number, low lubricity, and risk of engine corrosion developing in diesel-ethanol blends. 2-Ethyl Hexanol was added as a stabilizer; it is hydrophilic enough to avoid the phase separation of ethanol and diesel because of the polar and non-polar nature of the components. Its hydrocarbon structure imparts compatibility with diesel, while the oxygen functionality imparts strong hydrogen bonds with ethanol, ensuring the stability of the blend over a longer period of time. This property is critical for ensuring consistent fuel properties during storage and operation. Research, including studies by Di et al. [17], has confirmed that stabilizers are effective in maintaining the homogeneity of blends. One such stabilizer, 2-Ethyl Hexyl Nitrate, serves as a cetane improver. It is added to counteract the significant decrease in the cetane number caused by ethanol, which has a very low cetane number of around 8, compared to diesel fuel with a cetane number of about 51. By improving the ignition quality of the mixture, 2-Ethyl Hexyl Nitrate reduces ignition delay and enhances combustion efficiency. It also works as an oxidation promoter, which helps to lower CO and HC emissions in combustion [13]. This duality in function makes it indispensable in maintaining performance and keeping emissions low for ethanol-diesel blends. The addition of Ethomeen is due to the very poor lubricating properties of ethanol. Ethomeen could enhance the lubricity of the blend, apart from acting as a corrosion inhibitor that saves the wear and tear of different components in the engine. Better lubricity promotes durability for the engine under high-load conditions. Biodun et al. [21] explained the importance of such lubricants in a blended fuel.

The property of oxygenation in diesel-ethanol blend inherently improves combustion itself due to more complete fuel oxidation, hence with less soot and CO emissions. At the same time, this requires the use of complementary additives, such as 2-Ethyl Hexyl Nitrate, for maintaining combustion efficiency by balancing the reduction in cetane number. Hence, only the percentage of the second constituent was varied across various blends as shown in Figure 3.

Figure 4 shows the fuels and additive used in the present study.

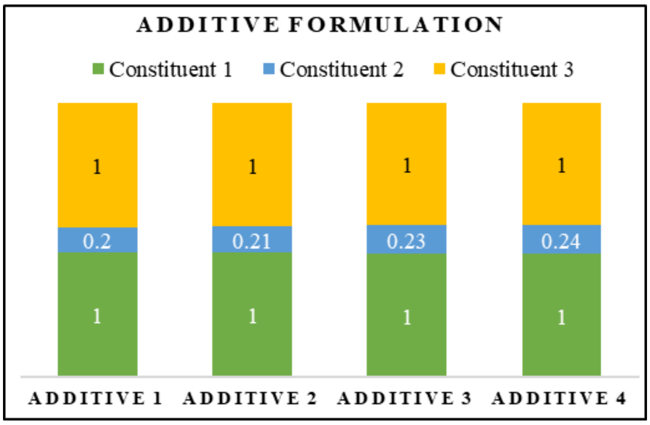

Figure 3. Additive formulation

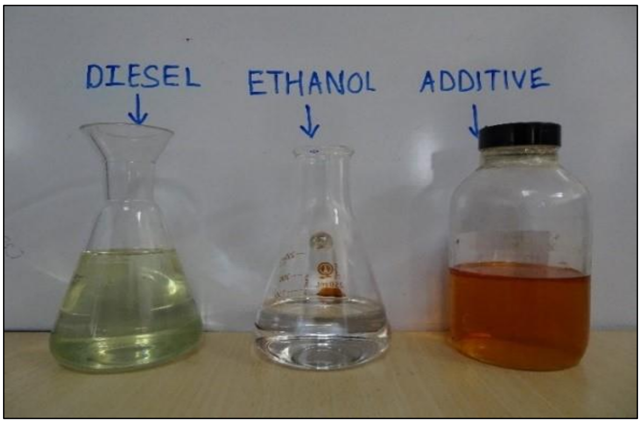

Figure 4. Diesel, ethanol, and additive

In the present study, the proportion of 2-Ethyl Hexyl Nitrate was changed in the blends (ED1, ED2, ED3, and ED4) and that of 2-Ethyl Hexanol and Ethomeen were maintained constantly. This was done to isolate the effects of cetane number on engine performance and emissions. The primary reason for this decision is the significant influence of cetane number on combustion processes. By keeping the stabilizing and lubricating functions constant, the study holds any changes in the related performance metrics, such as ignition delay, NO_x emissions, and smoke, to be fully due to the change in cetane enhancement. Moreover, ethanol's profound effect on cetane reduction requires the precise optimization of cetane improvers [9].

Figure 5. Stirrer used for blending

The four additive compositions used to prepare the four blends ED1, ED2, ED3 and ED4 were prepared by mixing constituents 1, 2 and 3 in proportions of 1: 0.20: 1, 1: 0.21: 1, 1: 0.23: 1 and 1: 0.24: 1 by weight respectively. The same ratio of diesel to ethanol to additive for all of the blends-a fixed weight percent of 90.3:7.7:2 - allows a controlled experiment in which the ability to measure performance benefit from changes in cetane improver is not obscured by instability issues of the blend or lack of lubricity.

The process of blending first involved the addition of ethanol to diesel fuel, followed by thorough mixing and introduction of additives to create the desired blend of diesel and ethanol. This blend was mixed through a stirring arrangement using a mechanical pump and stirrer, as shown in Figure 5.

3.2 Properties of blends

The blends prepared in the present study were tested for their properties as per IS 1460 standards. These properties included density, kinematic viscosity, flash point, sulfuric content, cetane number, gross calorific value, and water content. Initially, engine performance and emission testing were performed with ED7.7 blends having four different additive compositions. The engine performance and emissions were analyzed to identify the best-performing blends. Fuel characterization was performed for these best-performing blends. Table 1 shows the properties of base diesel, ethanol, ED7.7 blend without additives, and ED7.7 blend with additives 1 and 2. The importance of these properties is explained in brief as follows.

Table 1. Diesel-ethanol blend fuel characteristics

Properties	Unit	Diesel	Ethanol	Diesel Ethanol (ED7.7) without Additive	Diesel Ethanol (ED7.7) with Additive 1 (B1)	Diesel Ethanol (ED7.7) with Additive 2 (B2)
Density @ 15°C	kg/m³	826	789	811	811	811
Kin Viscosity @ 40°C	cSt	2.32	1.13	2.01	2.08	2.08
Flash Point	°C	42.8	11	13	13	13
Sulphur Content	ppm	9.5	9	7.6	6	6
Cetane Number	--	51	8	28	50.4	50.8
Gross Calorific Value	Cal/g	11010	6385	10671	10676	10677
Water Content	mg/kg	103	--	231	153	152

3.2.1 Density

Density is a critical physical property because it affects various aspects of the fuel's behavior, such as its energy content, combustion characteristics, etc. The density of neat diesel and neat ethanol is 826 kg/m^3 and 789 kg/m^3 respectively. Therefore, the overall density of the blend decreases when ethanol and diesel are combined. It was found that the ED7.7% blend has a density of around 811 kg/m^3. Diesel-ethanol blends showed decreased density mainly due to the lower density of ethanol compared to diesel. This means that less ED blend can be stored compared to diesel when stored in the same volume, and fuel system dynamics need to be addressed. Additive addition directly does not affect the density of the blend.

3.2.2 Kinematic viscosity

Kinematic viscosity is a measure of how easily a fluid flows under the influence of gravity. It describes how thick or thin a fluid is in terms of its flow behavior, regardless of its density [22]. High kinematic viscosity fluids flow more slowly and are often referred to as thick or viscous, while low kinematic viscosity fluids flow more quickly and are described as thin or watery. The neat diesel has a kinematic viscosity of 2.32 cSt, but when ethanol was blended in diesel, the kinematic viscosity decreased to 2.01 cSt. However, with the addition of the additive selected in the present study, the kinematic viscosity of the blend improved to a certain extent. The kinematic viscosity was increased to 2.08 cSt with the additive. There are both pros and cons associated with this decrease in kinematic viscosity. The reduction in kinematic viscosity is expected to enhance fuel atomization, improve combustion, and increase combustion efficiency; however, the effects on long-term engine performance and wear require careful evaluation.

3.2.3 Flash point

The temperature at which a fuel releases enough vapor to combine with air to form a combustible combination is known as its flash point. It is an important safety measure as it indicates the potential fire hazard associated with the fuel. Diesel fuel has a flash point of around 45°C, making it a Class-B fuel. On the other hand, ethanol has a flash point of around 11°C, which is less than the 23°C limit for Class-A fuels. When ethanol is blended with diesel, the blend takes on the properties of ethanol, resulting in a flash point of around 13°C. This is a major concern as the ethanol-diesel blend is then classified as Class-A, which requires special handling and attention to safely manage the potential fire hazard. On the other hand, lower flash points and higher volatility can improve fuel atomization and vaporization in the combustion chamber. To increase the flash point, the additive with higher carbon content needs to be added. In the present study, the additive does not impact the flash point.

3.2.4 Sulfur content

Sulfur is a natural constituent commonly found in crude oil, and its presence in diesel fuel primarily depends on the sulfur content of the crude petroleum oil used in the refining process. When diesel fuel contains high levels of sulfur, it contributes to environmental pollution and health hazards upon combustion. The combustion of high-sulfur diesel fuel releases sulfur dioxide (SO_2), which contributes to air pollution, acid rain, and respiratory diseases. To mitigate this issue, the sulfur level in diesel is limited to 10ppm from BSVI onwards. Furthermore, adding ethanol to diesel contributes to lowering sulfur levels, which is one of the advantages of using ethanol in diesel fuel. The sulfur content for diesel is about 9.5 ppm, and for diesel-ethanol blends, it is 7.6 ppm. Further, the addition of additives improves sulfur content to 6 ppm. The lower value of sulfur improves oxides of sulfur (SO_x) emissions. Also, the poising of after-treatment system can be reduced due to lower sulfur fuel. Lowering sulfur decreases the lubricity inside the engine cylinder, but it is well compensated by the addition of the additive.

3.2.5 Cetane number

The fuel's capacity to self-ignite and minimal ignition delay is measured by its cetane number. This has a considerable impact on the efficiency of fuel conversion, emissions of smoke, detonation, consistency of operation, and easy start-up [23]. Diesel fuel quality or performance is gauged by its cetane number. The higher the number, the better the fuel combusts within the engine. The cetane number of ethanol is 8, which is significantly lower than that of diesel, which is 51. Because ethanol is present in diesel-ethanol fuel, the cetane number significantly decreased. It was discovered that the blend's cetane number increased with the addition of the selective additive. The addition of additive 1 improves the cetane number from 28 to 50.4, and the addition of additive 2 further improves it to 50.8. This significantly helps ethanol-diesel blends to decrease ignition delay. The increased mixing time gives more time for the charges to mix with air and hence results in more combustion efficiency and less unburned hydrocarbon emissions.

3.2.6 Gross calorific value

The number of calories produced when a unit of a substance is fully oxidized is known as the calorific value. On a volumetric basis, ethanol's calorific value is 42% lower than that of a typical diesel fuel. The volumetric energy density of diesel decreases when ethanol is added in direct proportion to the fuel's ethanol content [22]. The calorific value of the diesel and diesel-ethanol blend was observed as 11010 and 10676 Cal/g, respectively. ED blend shows around a 3% reduction in calorific value. This means that an engine fueled with an ED blend may produce less power or a higher fuel quantity will be required to diesel equivalent power, leading to deterioration in the BSFC.

3.2.7 Water content

The amount of water in the mixture will rise when more ethanol fuel is introduced to diesel fuel since ethanol fuel is hygroscopic by nature. Diesel-ethanol blend solutions contain more water when ethanol is proportionately mixed with diesel fuel [22]. The level of stability and purity of combustion are impacted by the blends' steadily increasing water content, which has an impact on how well the diesel engine performs. The water content of ED blends is about 124% more than diesel. So, there might be chances of corrosion due to this additional water content. Hence additive needs to address the issue of higher water tolerance. Water tolerance can be improved with addition of additive.

3.2.8 Blending issues (Stability and phase separation)

Diesel is non-polar and ethanol is polar, which causes them to not mix properly due to their density differences. Furthermore, because ethanol has a higher hygroscopic tendency, particular precautions need to be undertaken while storing diesel-ethanol blends for extended periods of time. With the help of suitable additives, a more stable blend can be achieved [24].

The variation in additive composition through ED1 to ED4 resembles a balanced effort on the various trade-offs that ethanol blending introduces on both performance and emissions. An increase in viscosity and cetane number with higher additive blends increases combustion efficiency, reduces ignition delay, and NO_x and particulate emissions. However, the calorific value remains lower, along with increased water content, which challenges long-term operational stability. These findings indicate that improved additive formulations can overcome these difficulties without major engine redesigns, a further step toward the goal of providing greener fuel options.

A schematic illustration of a diesel engine testing laboratory used to examine engine performance, emissions, and combustion characteristics is shown in Figure 6.

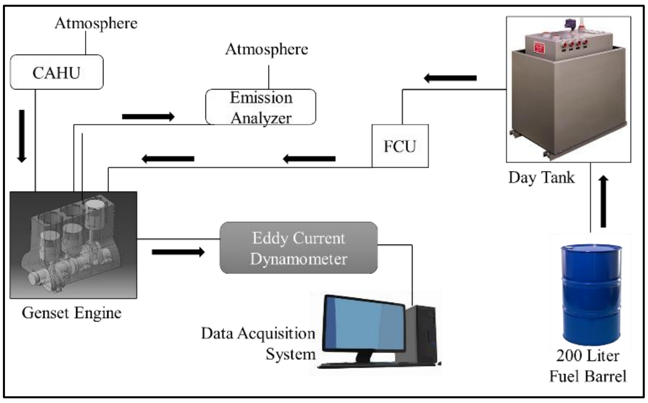

Figure 6. Experimental test setup and layout

This experimental setup was designed to perform engine tests on both standard diesel as well as diesel ethanol blends of ED7.7. The engine was initially mounted on a test bed using anti-vibration mounts. Then, it was connected to an eddy current dynamometer using a drive shaft. The dynamometer was employed to exert the required load on the engine at a specific engine speed. Table 2 provides a list of the test engine specifications. During the trials, temperature thermocouples were used to measure the temperatures of the engine lubricating oil, coolant, and exhaust gases.

Table 2. Engine specifications

Engine Specifications	Parameter
Make, Model	TM, RE01
Engine Type	Compression Ignition (CI)
Engine Configuration	Inline
No. of Cylinders	3
Cubic Capacity (cc)	3000
Engine Type	Multi-cylinder
Rated Speed	1500 RPM
Application	Stationary Engine
Emission Compliance	CPCB II

To keep the engine temperature consistent, a coolant conditioning system was used. For each test, the maximum temperature of the coolant was maintained at 82°C ± 2°C and the oil temperature was maintained at 120°C ± 2°C before starting the actual test. The intake air at 25°C ± 2°C at 100 kPa pressure was provided by using a conditioned air system. The usage of fuel was measured on a mass basis. The engine was supplied by mixtures of diesel and ethanol using a specialized fuel arrangement. The exhaust emissions levels of HC, CO, PM, and NO_x were measured using an exhaust gas analyzer. A smoke meter was used to test the opacity of the smoke in both steady-state and free acceleration modes.

The test lab's primary components comprised an engine, a fuel supply unit, temperature monitoring equipment, a condition air system, a fuel consumption meter, PM equipment, and a fuel conditioning valve. The equipment's used during this test are listed in Table 3.

Table 3. List of equipment's used in the experimentation

Equipment	Make
Engine dynamometer	Steady State Dyno – TC 12
Conditioned air system	K&S, CAS – 01
Air flow meter	SFI – 09 (ABB SENSYFLOW)
Fuel flow meter	CMF-01, dynamic
Exhaust gas analyzer	AVL AMAi60
Smoke meter	AVL 437
PM equipment	AVL, SPC - 472-05

Table 4 displays the engine performance measurement uncertainties at 95% confidence levels for the different measured parameters.

Table 4. Measurement uncertainty for engine performance parameters [25]

Sr. No	Engine Performance Parameters	Uncertainty value (@ 95 % confidence level)
1.	Nominal Speed	± 3.5 rpm
2.	Nominal Torque	± 2 N-m
3.	Nominal Power	± 0.5 KW
4.	Fuel Flow	± 0.05 kg/hr

The above-detailed experimental setup was utilized to test engine performance using the various diesel-ethanol blends prepared in the present study. The performance characteristics of the engine, such as its speed, torque, and fuel consumption, were recorded, and BSFC values were computed. In measuring equipment, the uncertainty of the data measurement is an inevitable stochastic process.

The base diesel and the ED7.7 blends were tested under different engine speeds as per the governing cycle as well as the ISO 8178 5-Mode regimes [26]. The speeds and torques of all points of operation during the 5-mode test cycle are listed in Table 5.

Table 5. ISO 8178 5-Mode cycle and its specifications

Mode No.	Constant Engine Speed (RPM)	Load %
1	1500	100
2		75
3		50
4		25
5		10

In this test, the engine is made to run at a steady speed of 1500 RPM. The present research work investigated engine performances at five points of engine torques viz. 10%, 25%, 50%, 75%, and 100%. The weighing factor percentages of these five points are shown in Figure 7.

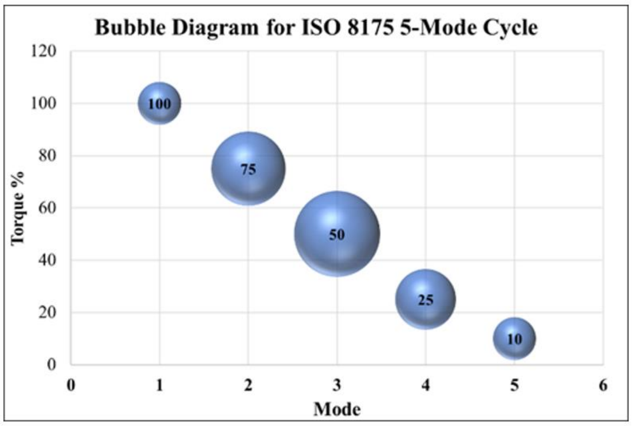

Figure 7. Bubble diagram for ISO 8178 5-mode cycle

During testing, the engine was set to 1500 rpm with full throttle. The torque corresponding to this mode is considered as full load torque. This was defined as mode 1 of the test cycle. Thereafter, mode 2 was set at 1500 rpm and 75% of the full load torque. Subsequently, modes 3, 4, and 5 were derived by keeping the same RPM, i.e., 1500 rpm with loads equivalent to 50%, 25%, and 10% of full load torque, respectively. Each mode of this test cycle comprised 10 10-minute duration each. Various performance parameters, such as airflow, fuel flow, temperatures, and exhaust emission, were captured for each mode.

3.3 Chemical interactions

The chemical interactions involved in diesel, and ethanol when combusted individually and for the ethanol-diesel blend are elaborated in a subsequent section.

3.3.1 Diesel combustion

Diesel is basically a higher hydro-carbon fuel derived from crude oil. It is a hydrocarbon mixture containing compounds containing carbon chains ranging from 8 to 25 carbon atoms. The combustion of the hydrocarbon ($C_{12}H_{23}$) with oxygen follows a multi-step mechanism. Initially, the fuel vaporizes and mixes with oxygen in the combustion chamber. Upon ignition, the heat breaks the carbon-hydrogen and carbon-carbon bonds in ($C_{12}H_{23}$), generating reactive radicals. These radicals initiate a series of chain reactions, where they rapidly react with oxygen molecules. The hydrocarbon's carbon atoms are oxidized to form carbon dioxide (CO_2), while the hydrogen atoms react with oxygen to produce water (H_2O). The overall reaction is exothermic, releasing significant energy, which sustains the combustion process and raises the temperature of the combustion products. The complete combustion of ($C_{12}H_{23}$) results in the efficient conversion of fuel into ($12CO_2$) and (11 H_2O), minimizing the formation of harmful by-products like carbon monoxide or soot under optimal conditions [27].

The combustion reaction can be written as Eq. (1).

$$C_{12}H_{23}+\frac{37}{2}O_2\rightarrow 12CO_2+11H_2O \quad (1)$$

3.3.2 Ethanol combustion

Ethanol is basically an alcohol-based fuel containing inherent oxygen in its chemical structure. The mechanism of ethanol combustion involves several key steps. Ethanol molecules are first vaporized and then mixed with oxygen. When ignited, the heat triggers a reaction that breaks the carbon-hydrogen and carbon-carbon bonds in ethanol. This process generates highly reactive intermediates, such as hydroxyl radicals. As the reaction progresses, these radicals facilitate the formation of carbon dioxide and water through a series of radical chain reactions. The radicals react with oxygen, leading to the formation of carbon dioxide as carbon atoms are fully oxidized. Simultaneously, hydrogen atoms combine with oxygen to form water. The reaction is exothermic, releasing energy that sustains the reaction and propagates the combustion process. Complete combustion occurs when there is sufficient oxygen, resulting in minimal by-products. However, if oxygen is limited, incomplete combustion may produce carbon monoxide and soot, highlighting the importance of optimal oxygen supply for efficient combustion [28]. Ethanol (C_2H_5OH) combustion can be represented by the following balanced chemical Eq. (2).

$$C_2H_5OH+3O_2\rightarrow 2CO_2+3H_2O \quad (2)$$

3.3.3 Diesel-ethanol blend combustion

The combustion of the ED7.7 blend, a mixture of ethanol and diesel, involves a complex chemical reaction mechanism that enhances fuel efficiency and reduces emissions. During the intake stroke in an internal combustion engine, the blend vaporizes and mixes with oxygen. Upon ignition, the heat breaks the chemical bonds in both the ethanol and diesel components, generating reactive radicals.

These radicals promote the oxidation of carbon and hydrogen, resulting in the formation of water and carbon dioxide. The presence of ethanol promotes a more complete combustion process, as it provides additional oxygen and enhances the oxidation of hydrocarbons found in diesel.

This improved combustion reduces the formation of harmful by-products, such as carbon monoxide and particulate matter, which are typically associated with traditional diesel fuel [29]. The exothermic nature of the reaction releases energy, powering the engine while contributing to lower overall emissions, making the ED7.7 blend a more environmentally friendly fuel option. The chemical reaction is shown in Eq. (3).

$$\begin{gathered}xC_{12}H_{23}+yC_2H_5OH+(237x+3y)O_2\\ \rightarrow(12x+2y)CO_2+(11x+3y)H_2O\end{gathered} \quad (3)$$

All the reactions shown by using Eqs. (1)-(3) are considering the complete combustion scenario where the ideal output is CO_2 and H_2O only. However, considering the real-life scenario, all the engines produce incomplete combustion due to various reasons, leading to the output of harmful pollutants like HC, CO, NO_x, PM, etc.

4. RESULT AND DISCUSSION

In this study, the emissions data corresponding to four different blends was compared and analyzed using bar graphs (Figure 8). Thereafter, the emissions and engine performance data corresponding to selected blends B1 and B2 were normalized for comparative analysis using various graphs shown in Figures 9-17.

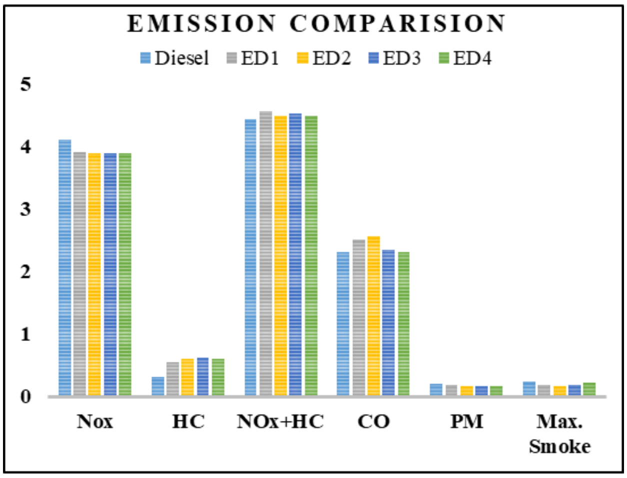

Figure 8. Emission comparison

4.1 Blend finalization

In this section, the performances of various diesel ethanol blends are presented and discussed, to finalize the best two blends for further detailed analyses. The emission performance results for base diesel, as well as different diesel ethanol blends, are shown in Figure 8.

The results show that NO_x levels for the ED blends were reduced as compared to base diesel. In case of HC, this trend was reversed, as there was increase in HC levels for all ED blend as compared to base diesel. The CO levels increased for ED1 and ED2, but decreased with further increment in the second additive constituent in the ED3 and ED4 blends. For smoke, there was a decreasing trend till ED3. However, maximum smoke increased in ED4, indicating that the second additive constituent cannot be increased after certain limit without risking higher smoke emissions. No significant differences were observed in the values of NO_x, NO_x+HC and PM across different blends. Marginal differences were observed in HC (lower in ED2), CO (lower in ED3 and ED4) and max smoke (higher in ED4). Hence, the ED1 and ED3 blends were selected for further detailed comparative analysis. These blends are henceforth referred to as blend B1 and blend B2 in the subsequent sections. It may be recalled that the blends ED1 (B1) and blend ED3 (B2) were prepared by mixing constituents 1, 2 and 3 combined together in the proportion of 1: 0.20: 1 and 1:0.23:1 by weight respectively.

4.2 Engine performance comparisons of selected blends

This section presents a detailed comparative analysis of the engine performance with the selected blends B1 and B2. The results are shown graphically and are normalized for better understanding and representation. The results are normalized for better understanding. Normalization involves transforming the data to a common scale, often between 0 and 1, to eliminate the effects of different units or magnitudes.

4.3 Governing trials

Figure 9 shows the results from the governing trials that were performed to check engine responses with respect to base diesel and ED7.7 blends B1 and B2. It was observed that the engine produced the same level of torque with blends B1 and B2.

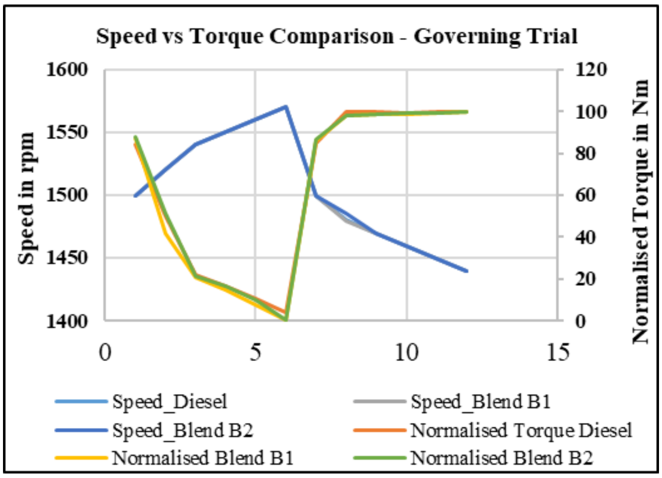

Figure 9. Governing test for speed v/s torque

4.4 Effect on BSFC

Figure 10 shows the relationship between torque v/s BSFC for both the fuels alongside base diesel. Due to greater temperatures and the resultant higher engine efficiency, the variation in BSFC was lesser at medium and lower loads than at higher loads. In general, genset is used at a constant speed cycle and is majorly loaded at 50%, 75% and 100%, hence fuel injection is advanced BTDC to obtain higher peak pressures.

Not much change was observed in the BSFC for both blends, however when compared with base diesel, they showed an acceptable difference. It is undeniable that when load increases, the BSFC drops, because the ignition delay of the diesel-ethanol blend fuel causes diffusion combustion. BSFC increases at lower loads because of reduced combustion temperatures. The BSFC values of B1 and B2 seem to be almost similar for high and medium loads but at the lowest load of 10%, the blend B2 has the highest value for BSFC.

In conclusion, the cycle BSFC with blends B1 and B2 deteriorated by 6.2% and 4.5% respectively when compared to base diesel.

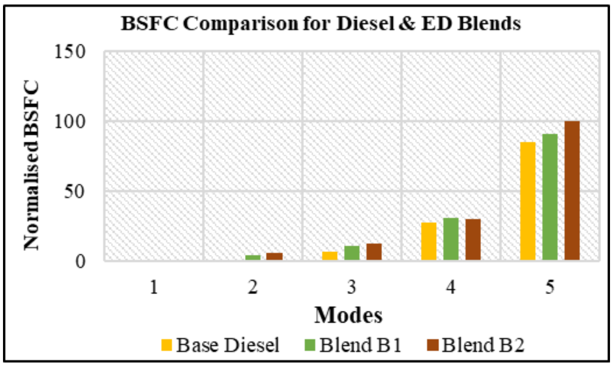

Figure 10. Torque v/s BSFC for diesel with blends B1 and B2

4.5 Effect on NO_x emissions

The relation between torque and NO_x for base diesel and the two blends B1 and B2 is shown in the Figure 11. NO_x emissions are influenced by combustion temperatures, which result in thermal NO_x generation, that can be avoided by achieving a more complete combustion. Therefore, oxygenating diesel with ethanol can improve the fuel's ability to burn more completely. Firstly, the alcohol's cooling impact reduces the combustion temperature which reduces NO_x generation because of its higher latent heat. Secondly, the oxygen percentage in the fuel makes it easier for thermal NO_x to form due to more rapid combustion and rise in peak cylinder pressures. In the present study, NO_x emissions were found to be lower for ED7.7 blends as compared to the base diesel, indicating a dominance of the alcohol's cooling effect over the detrimental effect of its oxygen content.

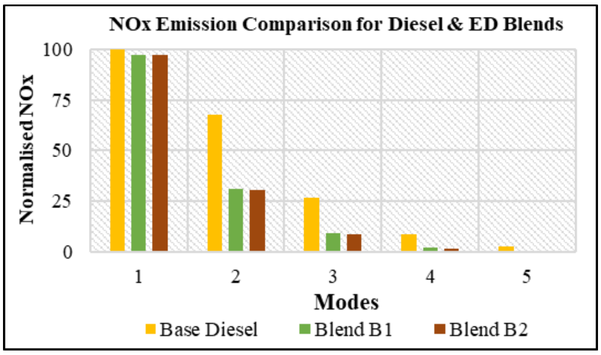

Figure 11. Torque v/s NO_x for diesel with blends B1 and B2

The combustion chamber's elevated temperatures and ample amount of available oxygen is what create NO_x emissions. Due to the high temperature created during combustion when using a significant amount of fuel, NO_x emissions tend to increase at increased loads. However, Ethanol has a higher latent heat of vaporization and a lower calorific value. Therefore, when it is burned, the combustion temperature decreases. As a result, the adiabatic flame temperature and NO_x emissions are reduced. In conclusion, the results show that no significant changes were observed among the two blends with regards to the NO_x parameter. However, the cycle NO_x of blends B1 and B2 was reduced by 30.7% and 29.8% respectively as compared to base diesel. Significant reduction in NO_x levels were also observed in 2nd, 3rd and 4th modes which contribute around 85% of the total cycle emissions.

4.6 Effect on HC emissions

The comparison of the two blends in terms of their effect on HC emissions is shown in Figure 12. The primary causes of unburnt hydrocarbon (HC) emissions are engine architecture, fuel composition, combustion temperature, oxygen availability, and residence duration.

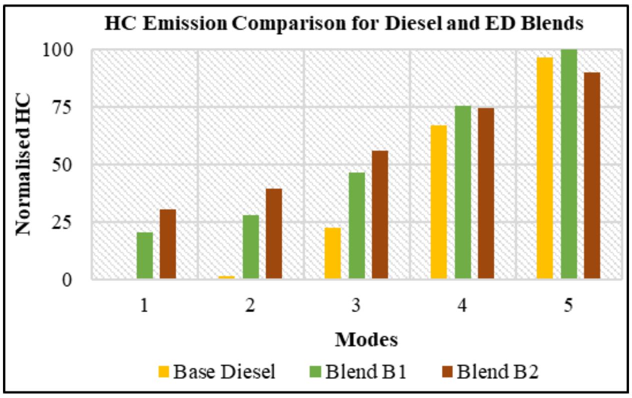

Figure 12. Torque v/s HC for diesel with blends B1 and B2

The trends in the HC emissions for Blends B1 and B2 were similar. Only under medium loads, some difference was observed among B1 and B2, but that too was negligible. However, HC emissions are higher for both the diesel-ethanol blends as compared to the base diesel. Unburned and partially burnt fuel emissions form THC. These THC emissions develop when fuel is left unburned as a result of flame front collision, which causes knocking. At lower loads, the B2 blend shows the lowest HC emissions whereas at the highest load, it shows highest emissions. In conclusion, the cycle THC with blends B1 and B2 increased by 22.1% and 27.9% respectively as compared to base diesel.

4.7 Effect on CO emissions

The following Figure 13 shows the effect of two blends (B1 and B2) on CO emissions. Both fuels demonstrate almost similar trend for CO emissions.

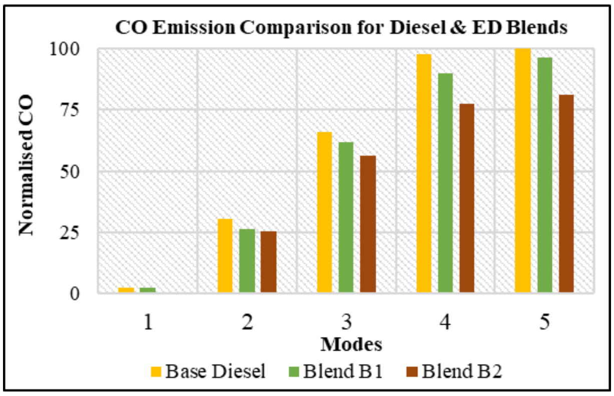

Figure 13. Torque v/s CO for diesel with blends B1 and B2

The emissions of B1 blend increased a bit for the overall loads as compared to the B2 blend. The base diesel showed the highest CO emissions for all modes. Diesel-ethanol blends generated lower CO emissions. This occurred due to the oxygen molecules breaking their bonds with the carbon in the ethanol molecule, causing them to split. Oxygen molecules aid in the completion of combustion, preventing the creation of CO that has only partially burned. Oxygen and carbon combine to make CO, more easily than any other molecule, which is completely burned with the help of oxygen to produce CO_2. The increase in load for diesel-ethanol blends led to a significant reduction in carbon monoxide (CO) emissions while operating at a constant rated speed. As the percentage of ethanol in the blend increases, the temperature in the combustion chamber decreases due to the high latent heat of ethanol vaporization. This, in turn, limits the oxidation of CO and raises CO emissions. However, at heavier loads, the oxidation of CO is enhanced by the higher temperature in the cylinder and the oxygen content of ethanol. As a result, the carbon monoxide emissions from diesel-ethanol blends are lower than those from pure diesel. In conclusion, the CO emissions with blends B1 and B2 were reduced by 5.1% and 12.5%, respectively, compared to base diesel.

4.8 Effect on smoke emissions and PM

PM and smoke emission results are shown in Figure 14 and Figure 15 respectively. In oxygenated fuel, the oxygen atom often forms a strong bond with the carbon atom that is difficult to break, preventing the production of aromatic hydrocarbons and black carbon. However, the ethanol's oxygen content, especially at high loads, can supply oxygen atoms in the combustion chamber and prevent smoke from forming. The smoke and PM emissions for the blends B1 and B2 blend were lower than those of base diesel. In comparison to base diesel, blends B1 and B2 had cycle PM reductions of 19% and 28.1%, respectively.

The cycle smoke with blends B1 and B2 was reduced by 29% and 38.2 %, respectively, as compared to base diesel.

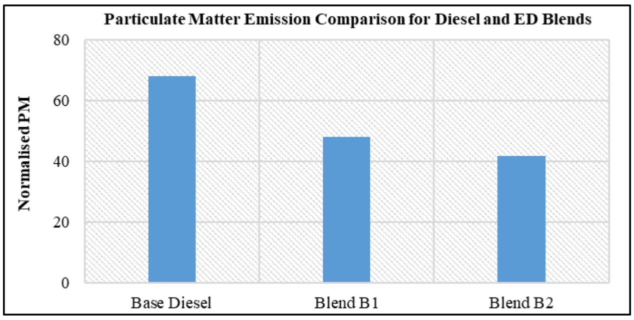

Figure 14. PM emissions for diesel and diesel-ethanol blends B1 and B2

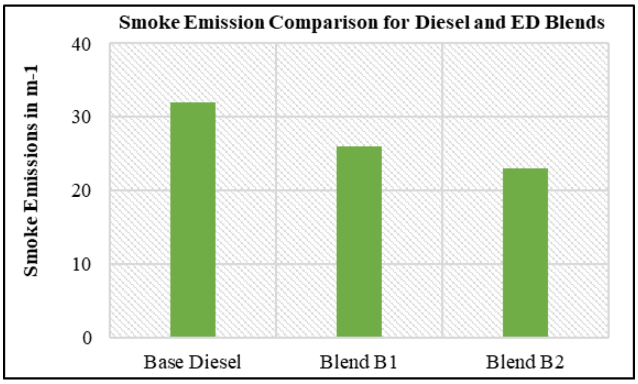

Figure 15. Smoke emissions for diesel and diesel-ethanol blends B1 and B2

4.9 Brake thermal efficiency

The Brake Thermal Efficiency (BTE) of an engine is a measure of how efficiently the engine converts the fuel's energy (calorific value) into useful mechanical energy (output). It is given by the following formula:

$$BTE = \frac{\text{Brake Power (BP)}}{\text{Fuel Flow} \times \text{Calorific Value}} \times 100$$

Figure 16 shows the comparison of BTE for base diesel and diesel ethanol blends B1 and B2. It can be seen that as the load of the engine decreased, the BTE also decreased, indicating inferior performance at lower loads. The primary reason for this occurrence is the incomplete combustion of the fuel, which results in a lower conversion of the fuel's energy into useful mechanical work. The figure shows that the Brake Thermal Efficiency (BTE) was slightly enhanced for the diesel-ethanol blend with additive B1 when compared to standard diesel. In contrast, the BTE for base diesel and the diesel-ethanol blend with additive B2 was comparable.

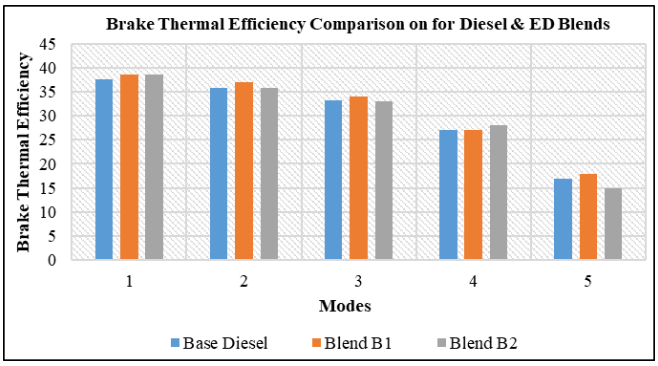

Figure 16. Brake thermal efficiency comparison for diesel and diesel-ethanol blends B1 and B2

4.10 Peak combustion pressure

Peak combustion pressure is a key combustion characteristic. Peak combustion pressure is the highest pressure reached inside the combustion chamber. For a diesel-ethanol blend, the peak combustion pressure is slightly higher than that of pure diesel due to an increased oxygen content and faster combustion.

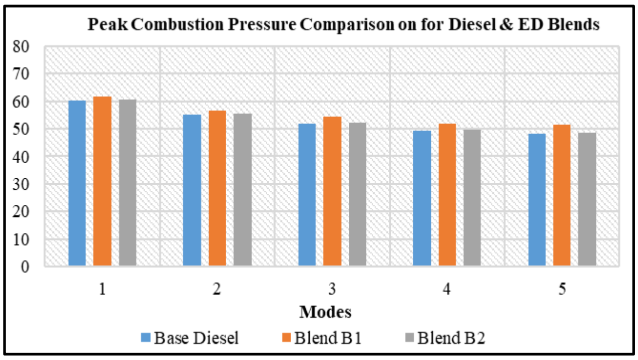

Figure 17. Peak combustion pressure comparison for diesel and diesel-ethanol blends B1 and B2

From Figure 17, it can be observed that the peak pressure was slightly increased for diesel ethanol blend with additive B1 when compared with diesel. Whereas BTE was comparable for base diesel and diesel ethanol blend with additive B2.

5. RESULTS COMPARISON WITH EXISTING LITERATURE

In this sub-section, the results discussed in previous sections are compared with other similar contemporary studies available in the literature.

Primarily, in the current study, a 3-cylinder engine was tested on a 5-mode cycle as per ISO standards with diesel and diesel ethanol blended with various additives. Based on the data analysis, the best blends (B1 and B2) were further considered for in-depth analysis. The current study reports that the cycle BSFC with blends B1 and B2 deteriorated by 6.2% and 4.5%, respectively, when compared to base diesel. As far as emissions are concerned, the cycle NO_x of blends B1 and B2 was reduced by 30.7% and 29.8%, respectively, as compared to base diesel, whereas the cycle THC with blends B1 and B2 increased by 22.1% and 27.9%, respectively, as compared to base diesel. Also, the cycle CO emissions with blends B1 and B2 were reduced by 5.1% and 12.5%, respectively, as compared to base diesel. In comparison to base diesel, blends B1 and B2 had cycle PM reductions of 19% had 28.1%, respectively. The cycle smoke with blends B1 and B2 was reduced by 29% and 38.2%, respectively, as compared to base diesel.

In the first comparison, Lü et al. [8] conducted an experimental investigation of engine emissions using a single-cylinder engine fueled with diesel and a diesel-ethanol blend. The engine underwent testing across an 8-mode test cycle. The authors reported reductions in CO and NO_x emissions of up to 21% and 7%, respectively, while total hydrocarbon (THC) emissions increased by as much as 50.5%. Notably, a significant decrease in smoke emissions was observed across all operating conditions when the diesel engine used ethanol-diesel blended fuels. Although the engine type, test cycle, and ethanol blending percentages in the present study differ from those used by Lü et al. [8], both studies show a reduction in NO_x, CO, and smoke emissions. Additionally, both studies reported an increase in hydrocarbon emissions.

In the second comparison by Klajn et al. [9], a motor-generating set having a single-cylinder engine was tested with diesel-ethanol fuel (1%, 5%, 10% and 15%) having bio-diesel (15% and 20%) as an additive at four different load points. The author observed that higher levels of ethanol resulted in lower nitrogen oxide (NO) emissions, which were statistically comparable to those of diesel fuel. Other pollutants were not in the scope of this particular study. Although the engine test cycle, engine type, and ethanol blending percentages in the current study differ from those used by Klajn et al., no significant differences in nitrogen oxide (NO_x) emissions were reported by their authors. In contrast, the present study found that NO_x emissions were reduced due to the additives used.

In the third comparison, Shanmugam et al. [10] conducted research on a single-cylinder compression ignition engine to evaluate its characteristics when fueled with a blend of diesel and ethanol. The additives used for testing were isopropanol, oleic acid, and ethylene acetate. The engine was tested at a constant speed of 1500 rpm under various load conditions of 25%, 50%, 75%, and 100%. THC and CO emissions were increased by around 15%, whereas NO_x was reduced by around 2%. This study also reported an increase in the THC and reduction in NO_x in line with the current study. However, a reverse trend was observed for CO when compared with the present study.

In the fourth comparison, Guo et al. [11] conducted studies to enhance the ignition capabilities and combustion characteristics of ethanol-diesel blended fuel (EDBF) to reduce the exhaust emissions from engines using this fuel. They selected ditert-butyl peroxide (DTBP) and 2-ethylhexyl nitrate (2-EHN) as cetane improvers. A four-cylinder diesel engine was used to perform this study. The engine was tested on 13 different points. The author found that CO and NO_x were comparable for diesel and diesel-ethanol blended fuel, whereas there was an increase in the observed HC levels. The result of this study also supports the findings of the current study.

In the fifth comparison, Pidol et al. [13] studied the properties of ethanol-blended fuels and evaluated their behavior in conventional diesel combustion. The single-cylinder engine was tested at 10 different operating points. The study shows that there was a reduction in the NO_x, CO, and smoke levels and an increase in the HC levels drastically. These results also validate the trend of emissions obtained in the current study.

6. CONCLUSIONS, NOVEL CONTRIBUTIONS AND POTENTIAL LIMITATIONS

This study presented a detailed engine performance analysis of different diesel ethanol blends, varying by compositions of the selected additive. Primarily, the performer enhancer constituent was varied across additive compositions to achieve four different variations of the ED7.7 blend. All blends were prepared and primarily tested under 5-mode cycle regime. Results demonstrate that optimized additive formulations simultaneously reduced the emissions by a large percentage margin with satisfactory engine performance. Of the blends researched in this paper, B2, with an additive composition of 1:0.23:1, was found to be the best blend that provided considerable emission reductions compared with base diesel.

The overall emission performances of the four blend variants were compared, and the two best-performing blends, ED1 (B1) and ED3 (B2) were selected for further detailed 5-mode analyses. Primary results indicate that:

1. Under governing trials, the engine produced the same level of torque with blends B1 and B2.
2. The cycle BSFC with blends B1 and B2 deteriorated by 6.2% and 4.5%, respectively, as compared to base diesel.
3. The cycle NO_x with blends B1 and B2 was reduced as compared to base diesel. This was because of the cooling effect caused by ethanol and its capability to reduce combustion temperatures. Significant reductions in NO_x levels were also observed in the 2nd, 3rd, and 4th modes of the 5-mode cycle, which contribute around 85% of the total cycle emissions.
4. The cycle HC with blends B1 and B2 increased as compared to base diesel. This was because of underscoring the unburned fuel fractions owing to the lower ignition quality and higher volatility of ethanol.
5. The cycle CO emissions with blends B1 and B2 were reduced as compared to base diesel. This underlines the advantages due to oxygen content in ethanol which helped to enrich carbon oxidation during combustion.
6. The cycle PM of blends B1 and B2 reduced as compared to base diesel. This can be attributable to the oxygenation effect of ethanol, which promotes more complete combustion.

The results presented in this study establish that the selection of a suitable additive composition is critical to achieving optimum engine performance and emissions. Additives used in this study can be further optimized based on their constituents to further reduce the emissions and improve performance. Additionally, by considering the chemical composition of diesel fuel, additive selection and research can be enhanced to achieve optimal composition(s).

Novel contributions of the study

This study demonstrates a significant advancement in sustainable energy solutions by focusing on ethanol-blended fuels like ED7.7. The findings emphasize three main aspects:

Optimised additive formulaiton

Research shows that appropriate additive compositions can improve the properties of diesel-ethanol blends. This enhanced blend can match diesel-like performance while significantly reducing pollutants such as CO, NO_x, and particulate matter.

Ease of adaptation

It was found that the in-use genset engines can be easily adapted with ED7.7. This can be achieved without requiring any substantial changes to the engine's existing hardware like piston bowl, compression ratio, and fuel system. The compatibility of ED7.7 with in-use genset engines reduces the cost and complexity of switching to cleaner fuel alternatives, making it a practical solution for widespread adoption.

Reduction in emissions

It was observed that with ethanol-blended fuel (ED7.7), harmful emissions can be lowered significantly when compared to conventional fossil fuels. This includes reductions in pollutants like HC, CO, and PM. The inclusion of ethanol, a renewable resource, not only enhances combustion efficiency but also minimizes the environmental impact of fuel usage.

Overall, this study underscores the dual benefit of using ethanol-blended fuels: maintaining operational efficiency while supporting global efforts to mitigate air pollution and promote sustainability. This study shows that an in-use genset engine can be easily used with ED7.7 without any major modifications in the fuel system.

Potential limitations for using diesel-ethanol fuel

Below are some of the challenges that might limit the implementation of diesel-ethanol blends as a fuel in the automotive sector.

Class-a fuel classification

With the addition of ethanol to diesel, the flash point of the blend decreases below 23°C, causing this fuel to fall into the Class-A category. As a result of this change, there will be handling restrictions for this blended fuel in bulk, similar to gasoline.

Low energy content

Ethanol has a lower energy content compared to diesel, which can lead to reduced fuel efficiency and power output when using higher ethanol blends. As a result, more fuel is needed to achieve power levels similar to those of diesel, leading to increased fuel consumption.

Cold startability issue

Ethanol is more susceptible to phase separation in cold temperatures, leading to fuel stability issues and challenges starting the engine in colder climates.

Infrastructure challenges

The current fuel distribution infrastructure may not be adequately equipped to handle diesel-ethanol blends, which could limit availability and convenience for consumers.

Availability of ethanol

Even with a blending percentage of 7.7%, the existing nationwide consumption of diesel fuel indicates that a large amount of ethanol will be needed to meet the blending requirement.

Cost considerations

In some regions, the costs of producing and distributing diesel-ethanol fuel may be higher than those of traditional diesel, which could impact its market competitiveness. Additionally, the costs may vary based on the ethanol production process.

7. FUTURE RESEARCH AREAS

- Further studies can be conducted with more sophisticated additive formulations to offset the increases in HC emissions without sacrificing the NO_x, PM, and CO benefits gained from the fuel blend B2.
- The study of modified injection timing and/or compression ratios might further optimize the combustion process and reduce the BSFC penalty for ethanol blends.
- Higher ethanol percentages (>10%) can also be researched for further reductions in emissions while maintaining stability and miscibility.
- Higher ethanol percentages (>10%) could be studied while maintaining stability and miscibility for further reduction in emissions.
- Full-scale evaluation of the effect of ethanol-diesel blends on engine wear and corrosion is necessary under prolonged operating conditions for wider acceptance.
- Feasibility to other types of engines, like heavy-duty or variable-speed engines, will validate the universality of the proposed additive compositions.

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