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Performance-Emission Analysis of a CI Engine Operating on D95 Diesel-n-Butanol Mixtures: An Experimental and Simulation Approach

Agboneni, O. [a], Adekunle, S. O. [b] and Ejilah, I. R. [c*]

[a] School of Engineering, Computing and Mathematics, Oxford Brookes University, Oxford, United Kingdom.
[b] Department of Mechatronics Engineering Technology, Federal Polytechnic, Bauchi, Nigeria.
[c] Department of Mechanical/Production Engineering, Abubakar Tafawa Balewa University, Bauchi, Nigeria.

Authors' contributions

This work was carried out in collaboration among all authors. Author AO designed the study, wrote the protocol and generated the first draft of the manuscript. Authors ASO and EIR conducted the test, interpreted the results and managed the analyses of the study. Author EIR managed the literature searches and reviewed the final draft of the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Aims: This study aims to analyze the impact of diesel-n-butanol fuel blends on the performance and emissions of a 4-stroke diesel engine, with an emphasis on assessing the efficiency and emissions improvements of the D95 blend through experimentation and simulation procedures.
Study Design: Performance evaluation was conducted in compliance with SAE J1349 test standards, using a Tec-Quipment TD110-115 4-stroke engine running at 1500 rpm. The GT-Power

**Corresponding author: E-mail: irejilah@atbu.edu.ng, rejilah@gmail.com;*

simulation toolkit was also employed to analyze different loads, using the D95 diesel-n-butanol blend and conventional diesel fuel.
Place and Duration of Study: The study was conducted over a span of 2 months at the Automotive Engineering Technology Workshop, Federal Polytechnic, Bauchi, Nigeria.
Methodology: The study followed the SAE J1349 test protocol, utilizing a D95 diesel-n-butanol blend and conventional diesel fuel. Engine setup, performance, and emissions were assessed through experimental procedures and GT-Power simulations. Despite its lower calorific value, the D95 blend exhibited performance comparable to that of diesel fuel.
Results: The combined findings from both experimental and simulation analyses provided insights into the effects of n-butanol-diesel blends on engine attributes, combustion, and emissions. However, simulated torque and brake power consistently exceeded experimental values as the engine load increased. While the D95 blend exhibited brake power comparable to that of diesel fuel, it also improved performance efficiency, fuel economy, and reduced emissions. Therefore, it is expected to promote sustainability and environmentally friendly fuel choices in the transportation sector.
Conclusion: The synergy of experimental and simulation results offers valuable insights into the effects of the diesel-n-butanol blend on engine performance, emissions, and fuel efficiency, while also improving the power output potential and providing sustainable fuel options.

Keywords: Diesel engine; D95 diesel-n-butanol blend; engine performance; fuel economy; emissions.

1. INTRODUCTION

Many researchers have evaluated the performance and emissions of CI engines with diesel-n-butanol blends. It was reported that Han et al. [1] studied a diesel-n-butanol blend in a multi-cylinder CI engine, showing enhanced combustion efficiency and reduced emissions of NOx and PM. Zhang et al. [2] found similar results for a single-cylinder CI engine, emphasizing improved combustion efficiency and decreased NOx emissions through n-butanol blending with diesel fuel. Diesel engines are commonly employed in various industries such as construction, agriculture, transportation, power generation, and industrial sectors primarily for generating power. Several factors, including higher efficiency, versatility, robustness, and lower operating costs, contribute to the preference for diesel engines over spark ignition counterparts [3]. The combustion of petroleum crude and its derivatives with long carbon chains in internal combustion engines results in the emission of significant amounts of CO2 into the atmosphere. This greenhouse gas traps heat and contributes to global warming. One global strategy to address the challenges posed by harmful emissions and the depletion of fossil fuels is the substitution of renewable fuels [4]. However, a long-term concern is the availability and sustainability of these fuels. Renewable oxygenated compounds, such as alcohols, present viable alternatives in this context due to their cleaner combustion compared to fossil fuels [5,6].

N-butanol as a versatile renewable fuel could be produced from lignocellulose biomass, or fermentation [7]. It is a primary alcohol surrounded by four carbon structures and the chemical formula C_4H_9OH that has four structural isomers [8-12]. Lower alcohols such as methanol and ethanol, as well as higher alcohols like butanol, have been used to partially replace diesel in diesel engines. Butanol, in particular, offers several advantages over lower alcohols. These advantages include a higher cetane number, higher heating value, better miscibility with diesel, and lower heat of vaporization compared to other lower alcohols [13]. N-butanol stands out as a strong contender as a fuel additive for diesel engines, despite being less explored in diesel engine research. With modern production methods, butanol has become an affordable and environmentally friendly option [14]. Unlike shorter-chain alcohols, butanol has the potential to serve as a suitable substitute for gasoline and possesses a moderate cetane number, allowing for significant amounts of butanol to be incorporated into diesel fuel [15-19]. Butanol is particularly intriguing as a renewable biofuel because its properties closely resemble those of diesel fuel, unlike ethanol [20].

Several studies have been reported on the performance, combustion and emission of diesel -n-butanol blends in CI engines with impressive outcomes [21-25]. A lot more research papers were published on the combustion behaviour of binary and ternary blend mixtures of butanol/biodiesel/ and diesel; and butanol/biodiesel/ and diesel fuels [26-30]. The results showed that n-butanol blending led to improved combustion efficiency and reduced particulate matter (PM) emissions. Using simulation and modelling tools such as; computational fluid dynamics (CFD), and multi-objective optimization theory to investigate the combustion and emissions characteristics of a diesel-n-butanol blend in CI engines, and further provide a more profound understanding of the combustion kinetics of the butanol blended fuel samples in CI engines was also reported with significant success [31-33]. Xu, *et al.* [34] used GT-Power to assess the impact of n-butanol blending, revealing improved combustion efficiency and reduced NOx and PM emissions. These simulations offer valuable insights into the effects of fuel blending on engine behaviour. Experiments validate simulation results, while GT-Power enables detailed analysis under diverse conditions. However, not many simulation studies were carried out on CI engines running on diesel-n-butanol fuel samples, as it was with spark ignition engines running on gasoline fuel and blends of oxygenated fuels. The preference for using GT-Power was to provide a comprehensive understanding of the engine's behaviour under various conditions, and a detailed examination of how blending diesel fuel with n-butanol affects crucial engine parameters, including combustion characteristics, power output, fuel efficiency, and emissions of pollutants such as NOx, PM, CO, and HC.

Hence, the main thrust of this research is to conduct a comprehensive engine performance and emission analysis of a CI engine using the D95 diesel-n-butanol blends through experimental and simulation approaches to provide valuable insights for alternative fuel development and influence of engine design, for more sustainable and energy-efficient transportation sector.

2. MATERIALS AND METHODS

2.1 Materials

The source of materials and properties of n-butanol used for this study are presented in Tables 1 and 2.

The use of personal protective equipment, such as; gloves, coveralls, and recommended respirators of >20ppm –full face piece APR with organic vapour cartridges, >200ppm- supplied air to deal with health and safety concerns against; inhalation, and eyes and skin contact would be encouraged when handling n-butanol and preparing fuel samples in the laboratory [35].

Table 1. Source of fuel and n-butanol additive

S/N	Material	Product Manufacturer /Distributor
1	Diesel	Nigerian National Petroleum Corporation, Nigeria
2	N-Butanol	Solventis, Surrey, UK.

Table 2. Technical properties of n-Butanol

Properties	Specifications
Description	Colourless liquid, medium volatility, banana-like odour
Synonyms:	butan-1-ol, 1-butanol, normal butanol, and n-butyl alcohol
Cas Number	71-36-3
Molecular Formula	$C_4H_{10}O$
Molecular Mass	74.12
Flashpoint (closed cup)	29 °C (84.2 °F) - 35 °C
Autoignition temperature	343 °C (649.4 °F)
Boiling Point	117 °C (242.6 °F)
Melting Point	-90 °C (-130 °F)
Vapour Pressure	0.58 kPa at 20 °C (68 °F)
Density	0.81 at 20 °C (68 °F)
Log P	0.88

Source [34]

2.2 Preparation of Fuel Samples

To prepare the samples for the study, different compositions of diesel and n-butanol were mixed with the aid of a mechanical-magnetic stirrer. For the purpose of this study, 4 separate samples of D95, D90, D85, D80, and D75 fuel mixtures were prepared at an ambient temperature of 36^{o}C and stirred for 60 minutes to obtain a homogeneous consistency. Each blended fuel sample was prepared on a volumetric basis of 500ml using the prescribed volumetric proportion of the mixtures in Table 3.

2.3 Fuel Characterizations

ASTM Standard test protocols as prescribed in Table 4 were used for the fuel property determination.

2.4 Engine Performance Test

The engine performance and emission characteristics of a Diesel-Butanol fuel mixture in a single-cylinder 4-stroke compression ignition engine were studied using both experimental methods and modelling and simulation techniques. The performance test was conducted in conformity with SAE J1349 and ISO 8178 test protocols [36,37] for evaluating the power output, torque, fuel consumption, and emission levels on a Tec-Quipment TD110-115 single-cylinder, 4-stroke air-cooled engine test rig coupled to a horizontal hydraulic dynamometer (refer to Fig. 1 and Table 5).

Table 3. N-Butanol -Diesel Blends

S/N	Samples	Fuel Constituents (%)	
		N-butanol	Diesel
1	D100	0	100
2	D95	5	95
3	D90	10	90
4	D85	15	85
5	D80	20	80
6	D75	25	75

Table 4. ASTM D975 test protocol for fuel samples

Fuel Property	ASTM Specification
Density at 40^{o}C (kg/m^3)	ASTMD4052
Specific gravity	ASTMD4052
Kinematic viscosity at 40^{0}C (mm^2/s)	ASTM D445
Flash Point (^{C})	ASTM D93
Cloud Point (^{o}C)	ASTM D2500
Derived Cetane Number	ASTM D613
Calorific Value (kJ/Kg)	ASTM D975
Autoignition temperature (^{o}C/^{o}F)	ASTM E659-14

Source: [38]

The engine was operated at a constant speed of 1500 rpm under varied and incremental loading conditions of 500g, 1000g, 1500g, 2000g, 2500g and 3000g at an interval of 20 minutes. The time taken by an engine to consume 8 ml of fuel, torque, exhaust temperature and barometric pressure for all fuel samples were recorded. As the fuel sample(s) were run, engine performance measurements such as brake specific fuel consumption, air flow rate, brake power, volumetric efficiency, brake thermal efficiency, percentage heat loss and air/fuel ratio were. The concentration of emissions of CO_2, CO, unburnt HC, and NO_X was measured using an SV-5Q automobile exhaust gas analyzer by fixing the probe tip of the exhaust gas analyzer to the exhaust tailpipe of the engine test bed.

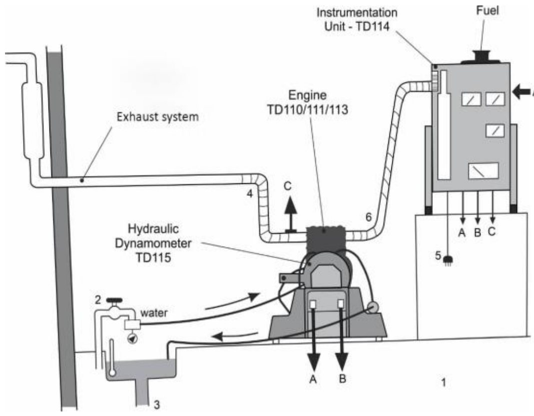

Fig. 1. An illustration of a complete TD110-TD115 TQ small engine test rig [39]

Table 5. Test engine technical specifications

Parameters	Specifications
Model	TD110-115
Number of cylinders	1
Method of starting	Manual starting
Engine type	Single-cylinder, 4-stroke diesel
Bore	79.5× 95.5 mm
Piston stroke	115mm
Displacement	1896mm
Rated speed	3600 rpm
Maximum output	5.6kW
Compression ratio	12:1 to 17.5:1
Maximum MEP	1400kPa
Cooling method	Air-cooled
Fuel and Lube oil	filter Present
Injection pump	Bosh VE VP 37

Source: [39]

2.5 Modelling and Simulation of Engine Characteristics

GT-Power was employed to define the engine configuration, specify fuel properties, model the intake system, configure combustion, analyze performance and emissions, and optimize operating conditions. The simulation yielded important information about engine performance and emissions. This comprehensive approach provided valuable insights into the behaviour of the fuel mixture in the engine. The GT-ISE modelling format, which utilizes an object-oriented structure, was employed to construct the engine model for analyzing performance and emissions [40]. This structure consists of three hierarchical levels: i) Templates, ii) Objects, and iii) Parts. To model the single-cylinder compression ignition engine, a total of eleven templates were developed. These templates include the Inlet environment, Intake runner, Intake port, Intake valve, cylinder (comprising the cylinder initial state object, cylinder wall temperature object, fuel injector), outlet environment, exhaust runner, exhaust port, exhaust valve, and engine crank train (incorporating the engine speed parameter, engine friction object, and cylinder geometry object). Once all the aforementioned templates were created, the parts were placed on the project map, and the components were interconnected, as depicted in Plate 1. Each object appearing on the map now functions as an individual part, with GT-ISE automatically assigning a name to each part as it is positioned on the map. Once the engine was modelled, specific input parameters for the case, simulation type, and desired output were specified in the settings menu of GT-ISE. To execute the model, the "Run Simulation" button on the GT-ISE toolbar was utilized, and the model was automatically saved for future reference. A sample of the simulation window is depicted in Plate 1, while the results of the simulation can be found in Plates 2, 3 and 4.

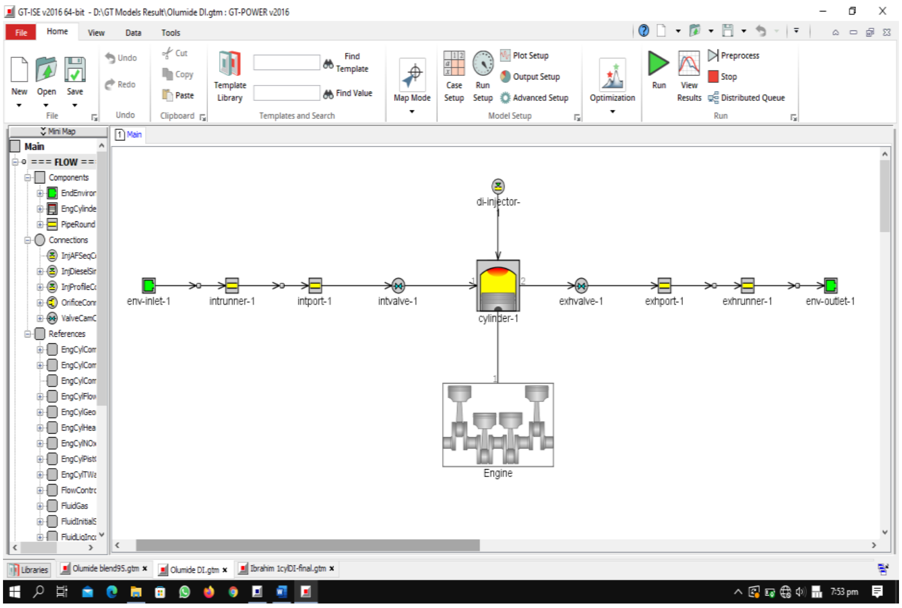

Plate 1. Engine model from GT-POWER Software

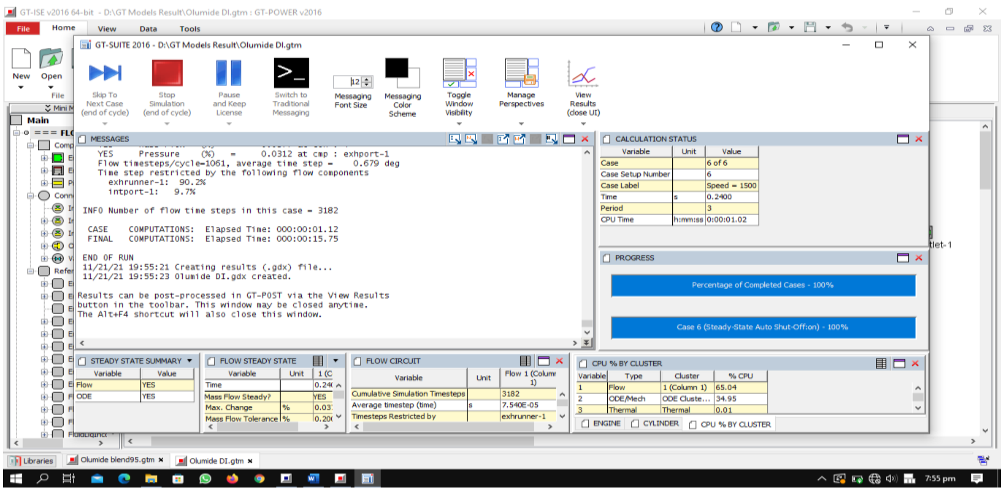

Plate 2. Simulation window output

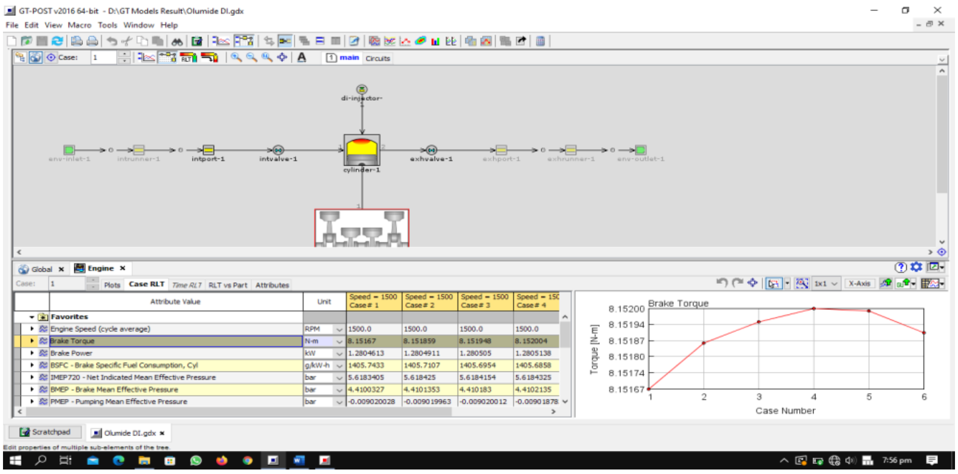

Plate 3. Results of the simulated model

Attribute Value	Unit	Case# 1	Case# 2	Case# 3	Case# 4	Case# 5	Case# 6
Favorites							
Brake Torque	N-m	3.9205763	8.225089	10.459965	11.881451	12.631191	13.111469
Brake Power	kW	0.24633707	1.0335952	1.9716569	2.9861343	3.968206	4.9429073
BSFC - Brake Specific Fuel Consumption, Cyl	g/kW-h	2192.1182	1044.8965	821.644	723.34326	680.40826	655.4847
BMEP - Brake Mean Effective Pressure	bar	2.1210217	4.4497523	5.6588144	6.4278345	6.8334427	7.0932713
Air-Fuel Ratio (Inducted Air/Total Fuel)		5.336082	5.7361803	5.9861765	6.186428	6.3004675	6.397205
Average of Maximum Cylinder Pressures	bar	73.39239	79.157845	81.41906	82.788055	83.83018	84.49621
Total Exhaust Energy Percentage	%	79.8077	78.7351	78.169914	77.68349	77.52651	77.37332
Useful Exhaust Energy Percentage	%	--	5.311702	11.620671	15.776746	18.337225	20.293995
Brake Efficiency, System	%	3.8088841	7.990763	10.161958	11.542937	12.271317	12.737906
NOx Concentration (ppm) - Cylinder Out	ppm	1252.7375	1498.1177	1657.3783	1762.4772	1820.0405	1847.0507
CO Concentration (ppm) - Cylinder Out	ppm	250488.81	235423.12	226218.88	219062.89	215027.58	211637.83
CO2 Concentration (ppm) - Cylinder Out	ppm	5328.5474	10993.262	14560.491	17399.508	19027.234	20410.111
Hydrocarbon Concentration (No C Basis) (ppm) - Cylinder Out	ppm	0.20092821	0.1944106	0.19089761	0.18819308	0.18628897	0.18484889

Plate 4. Simulated results from GT-POWER

To view and extract the results, the "Open GT-POST" button on the GT-ISE toolbar was clicked. Subsequently, the corresponding .gdx file with the same name as the model was selected. This action launched the GT-POST post-processing program in a new window, where available plots were extracted and compared with experimental plots for the variations of engine torque, brake power, brake specific fuel consumption, brake thermal efficiency, as well as emissions of CO_2, CO, unburnt HC, and NO_X with load increase, were analyzed for D95 fuel samples.

3. RESULTS AND DISCUSSION

3.1 Fuel Properties of Fuel and Blended Samples

Table 6 presents the results of the fuel sample properties, and are being discussed as follows:

According to the findings in Table 6, the diesel fuel sample exhibited a relatively higher fuel density and relative density at room temperature, measuring 0.836. It is notable that as the proportion of n-butanol additive in the fuel mixture increased, the density of the fuel samples decreased. In terms of kinematic viscosity, diesel fuel samples had the highest viscosity, measuring 2.98 mm²/s. Lower fuel viscosity indicates improved fuel injection, atomization, and combustion behaviour. Upon further analysis of the results in Table 6, it can be observed that diesel fuel samples displayed the highest flash point at 54°C, while the blended fuel samples (B100, D95, D90, D85, D80, and D75) progressively decreased to 37°C, 34°C, 32°C, 31°C, 31°C, and 30°C, respectively. The cloud point of the analyzed fuel samples revealed that diesel fuel samples had the highest pour point at -24°C, which decreased as the volumetric proportion of n-butanol increased in the fuel mixture. Low-temperature behaviour is crucial for engines during cold starts and low-load conditions.

The cetane number (CN) is a significant parameter that affects the behaviour of diesel fuel as it relates to the time elapsed between fuel injection and the start of combustion. A higher CN signifies a shorter ignition delay, causing combustion to commence shortly after injection into the combustion chamber, thereby increasing efficiency. The cetane number results indicated that diesel fuel samples exhibited the highest cetane number at 56.9, while the n-butanol blended fuel samples (D95, D90, D85, D80, and D75) had relatively lower values with readings of 52.7, 49.9, 49.1, 44.1, and 41.9, respectively. The B100 fuel sample had the lowest cetane number at 17.6.

In terms of the heating value of the fuel samples under examination, the diesel fuel samples had the highest value at 45,530.6 kJ, while the n-butanol blended fuel samples (D95, D90, D85, D80, and D75) exhibited relatively lower heating values of 44,728.4 kJ, 44,728.4 kJ, 44,126.9 kJ, 43,532.0 kJ, 43,321.5 kJ, and 42,579.7 kJ, respectively. The B100 fuel sample had the lowest calorific value at 37,025 kJ.

As for the auto-ignition temperature (AIT), which is the lowest temperature at which the fuel ignites spontaneously under ambient conditions without an external ignition source like a spark or flame, it is evident that butanol has a higher AIT value (343°C / 649.4°F) compared to the diesel fuel sample (210°C / 410°F). This implies that a higher temperature is required to provide the activation energy necessary for the combustion of butanol and its blends compared to diesel fuel. Consequently, a more rapid compression is necessary to elevate the temperature of butanol and its blends to initiate self-combustion of the fuel samples. As a result, butanol and its blended samples are considered safer for storage and transportation due to their higher AIT.

3.2 Comparison of Experimental and Simulated Performance Results

For the purpose of analysis, the D95 fuel mixture was chosen for experimental performance and emissions evaluation, as it outperformed other n-butanol blended fuel samples under study. Therefore, a comparison between the experimental and simulated engine performance and emission characteristics, obtained from the GT-Power model, is presented in Tables 7 to 9 and Figs. 2 to 9.

3.2.1 Effect on engine torque

The comparison between the experimental and simulated torque results for the D95 fuel sample is presented in Fig. 2. At loads of 500g, 1000g, 1500g, 2000g, 2500g, 3000g, and a constant speed of 1500 rpm, the simulated torque is 11.4%, 5.12%, 9.47%, 3.47%, 5.88%, and 1.55% higher than the experimental torque, respectively. This trend is consistent with the increasing torque values as the engine load rises.

Table 6. Fuel properties of n-butanol and diesel fuel blends

Fuel Property	D100	B100	D95	D90	D85	D80	D75
Density at 40^{o}C (kg/m^3)	835.6	813	833.79	832.78	831.03	829.62	828.70
Specific gravity	0.8367	0.813	0.8337	0.8327	0.8310	0.8296	0.8287
Kinematic viscosity at 40^{0}C (mm^2/s)	2.980	2.22	2.895	2.817	2.798	2.776	2.762
Flash Point (^{C})	54	37	34	32	31	31	30
Cloud Point (^{o}C)	-24	-	-34	-35	-36	-37	-37
Derived Cetane Number	56.70	17.6	52.70	49.90	47.10	44.10	41.90
Calorific value (KJ/Kg)	45530.6	37025	44728.4	44126.9	43532.0	43321.5	42579.7
Autoignition temperature (^{o}C/^{o}F)	210 °C (410 °F)	343 °C (649.4 °F)	-	-	-	-	-

Table 7. Experimental engine performance results of D95 fuel sample

S/N	Properties	Load (g)					
		500	**1000**	**1500**	**2000**	**2500**	**3000**
1	Speed (rev/min)	1500	1500	1500	1500	1500	1500
2	Torque (Nm)	3.0	4.4	6.5	8.7	10.8	11.0
3	Time taken for 8ml(s)	85.11	86.00	88.00	89.18	90.00	89.28
4	Brake power (kW)	0.47	0.69	1.02	1.37	1.69	1.72
5	Fuel mass flow rate (kg/hr)	0.282	0.279	0.272	0.269	0.266	0.268
6	Brake specific fuel consumption (g/kwhr)	2184.58	1154.58	837.53	721.03	677.31	652.84
7	Air /Fuel ratio	85.06	85.95	87.95	89.03	89.95	89.23
8	Brake specific energy consumption (MJ/kwhr)	97.71	51.64	37.46	32.25	30.29	29.20
9	Exhaust temp. (°C)	430	440	450	460	475	485
10	Brake thermal efficiency (%)	3.62	6.91	9.61	11.12	11.89	12.13

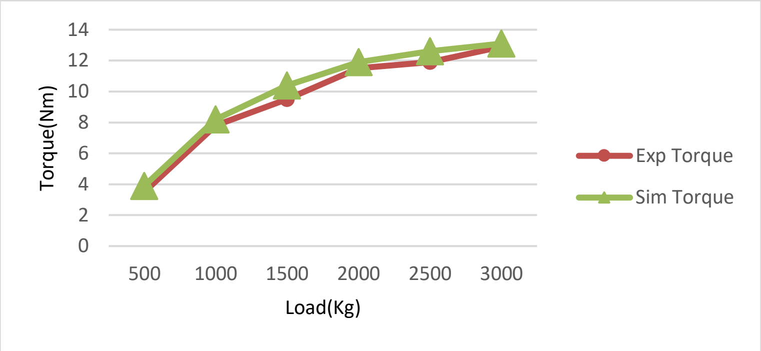

Fig. 2. Variation of engine torque with load increase for D95 fuel sample

3.2.2 Effect on brake power

Fig. 3 illustrates the relationship between brake power and load increase for both diesel and its blends with n-butanol. As the load increased to its maximum, an overall increase in brake power was observed for both diesel and its blends. The higher brake power delivered by the engine running on diesel fuel can be attributed to its higher calorific value, as indicated in Table 6. The brake power performance of D95 was found to be comparable to that of diesel fuel. However, at a load of 2500g the brake power for D95 decreased by 69.7% Furthermore, it declined to 72.8%, still lower than the brake power of the diesel fuel sample at the 3000g load. This reduction can be attributed to the improved calorific value of n-butanol when blended with diesel. On the other hand, the D85, D80, and D75 blends exhibited decreased brake power due to the decrease in heat release resulting from their lower calorific values. This reduction can also be attributed to the higher heat of vaporization of n-butanol, which leads to a decrease in power and torque [41].

Fig. 3 illustrates the behaviour of the experimental and simulated brake power for the D95 sample. At a 500g load, it was observed that the simulated brake power is 9.22% lower than the experimental brake power. However, at 1000g, 1500g, 2000g, 2500g, and 3000g loads, along with a constant speed of 1500 rpm, the simulated brake power is 4.33%, 8.30%, 16.32%, 7.33%, and 16.88% higher than the experimental brake power, respectively.

3.2.3 Effect on fuel economy

Fig. 4 demonstrates that as the engine load increased, the brake-specific fuel consumption (BSFC) decreased, reaching its minimum value at the 3000g engine load. The BSFC of the blended samples closely resembled that of diesel fuel at the 2000g, 2500g, and 3000g engine loads. At a load of 1000g, the BSFC for D95 decreased by 11.17% and further dropped to 0.024% at 3000g, which was lower than the diesel fuel sample. This improvement in BSFC can be attributed to efficient combustion resulting from the additional oxygen molecules present in

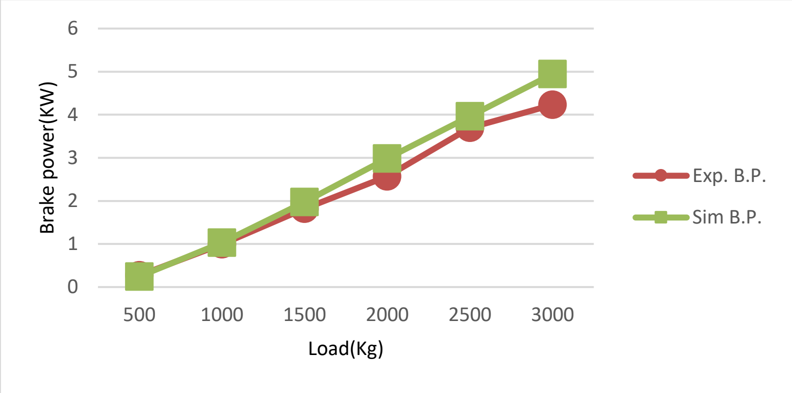

Fig. 3. Variation of BP with load increase for D95 fuel samples

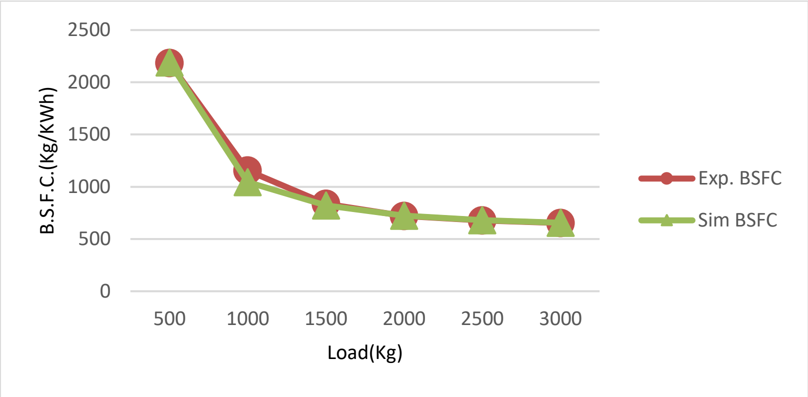

Fig. 4. Variation of BSEC with load increase for D95 fuel samples

the n-butanol within the blended fuel samples under investigation [42].

It was also observed from Table 7 that the BSFC values of diesel fuel were lower compared to the blended samples. In other words, as the percentage of n-butanol increased in the blends, the BSFC increased. The increased BSFC in blends with a higher n-butanol percentage can be attributed to the combined effects of lower calorific values, densities, and viscosities, which lead to a lower fuel flow rate (refer to Table 4). However, Kuszewski [43] suggested that a slight decrease in the density of n-butanol-diesel blends with an increase in the n-butanol fraction could pose a marginal issue in modern diesel engines. Nonetheless, this challenge can be overcome by modifying the control system to increase the mass fuel delivery at lower fuel density.

Fig. 4 provides a comparison between the experimental and simulated BSFC at a constant speed and variable engine loads. At the 500g load, the simulated BSFC is 0.34% higher than the experimental BSFC. At 1000g and 1500g loads, the simulated BSFC is 9.49% and 1.90% lower than the experimental BSFC, respectively. However, at loads of 2000g, 2500g, and 3000g, the simulated BSFC is 0.31%, 0.15%, and 0.41% higher than the experimental BSFC, respectively

3.2.4 Effect on fuel combustion

Fig. 5 illustrates that brake thermal efficiency (BTE) increases as the load increases for all tested fuel samples. This can be attributed to the corresponding increase in brake power resulting from improved combustion behaviour at higher engine loads, up to a maximum of 3000 g. The presence of oxygen in the blends may have enhanced the combustion of fuel samples at low engine loads. However, at high-loading conditions, the transition from molecular oxygen to atomic oxygen could potentially lead to a decrease in BTE [44]. BTE represents the engine's output in relation to the heat supplied by the fuel. Diesel fuel demonstrated higher BTE compared to the other tested blends under varying load conditions (refer to Fig. 5). This can be ascribed to the higher calorific value of diesel fuel (refer to Table 4).

At a load of 2500g, the BTE for D95 decreased significantly by 1.67% and further dropped to 0.11% lower than the diesel fuel sample at an engine load of 3000g. The fact that the BTE values for D95 at loads of 2000g, 2500g, and 3000g closely resemble those of diesel fuel suggests improved stoichiometric mixture and enhanced combustion behaviour of the fuel samples in the combustion chamber, likely due to the additional oxygenation effect of n-butanol in the fuel blends.

Additionally, the lower BTE obtained for D80 and D75 blends can be attributed to a combination of factors, such as the decrease in calorific values (refer to Table 4) and the increase in fuel consumption. The higher latent heat of vaporization of n-butanol may also hinder proper air-fuel mixing, resulting in inferior fuel combustion and lower BTE values [45]. The experimental and simulated BTE behaviour of the D95 sample is presented in Fig. 5. At 500g, 1000g, 1500g, 2000g, 2500g, 3000g, and a constant speed of 1500 rpm, the simulated BTE is 3.37%, 14.62%, 5.73%, 3.39%, 3.27%, and 3.32% higher than the experimental BTE, respectively.

3.2.5 Effect on gaseous emissions

While diesel engines offer numerous benefits, their use also brings about specific challenges. The combustion of diesel fuel leads to the release of CO2, NOx, and particulate matter, contributing to air pollution and a decline in air quality. Apart from these adverse environmental impacts, there are additional challenges related to the depletion of diesel resources and the uncertainty surrounding diesel prices [46]. However, this section presents the results of tailpipe emissions for the tested fuel samples, including CO2, CO, unburned HC, and NOx gases. These results are displayed in Tables 8 and 9 and visualized in Figs. 6 to 9. It can be observed from Tables 8 and 9 that CO2 emissions for D100 and D95 increase with engine speed, but the level is significantly lower for D95 across all engine speeds. Fig. 6 presents the comparative experimental and simulated results for CO2 emissions of the D95 sample. At 500g, 1000g, 1500g, 2000g, 2500g, 3000g, and a constant speed of 1500 rpm, the simulated CO2 emissions are 11.67%, 6.82%, 5.84%, 5.48%, 2.15%, and 3.03% higher than the experimental CO2 emissions, respectively.

It does suggest that the use of shorter-chain butanol, which has lower calorific values and cetane numbers, played a significant role in reducing CO2 emissions, improving combustion, and achieving stoichiometric ratios across all engine loads. Likewise, in Tables 8 and 9, it's evident that CO2 emissions decrease with engine speed for both D100 and D95, but D95 consistently exhibits significantly lower emissions across all engine speeds. This trend can be largely attributed to the shorter chain length of butanol in the fuel mixture and its oxygenation effect. Fig. 7 displays the comparison of experimental and simulated CO emissions for the D95 sample. At 500g, 1000g, 1500g, 2000g, 2500g, 3000g, and a constant speed of 1500 rpm, the simulated CO emissions are 13.64%, 9.09%, 15%, 15.79%, 16.67%, and 17.64% higher than the experimental CO emissions, respectively.

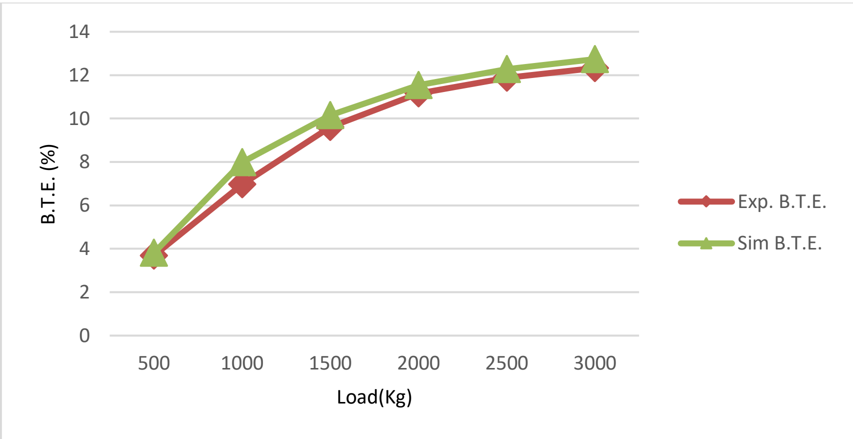

Fig. 5. Variation of BTE with load increase for D95 fuel sample

Table 8. Experimental engine emissions result from the D100 fuel sample

Emissions (ppm)	Load (g)					
	500	**1000**	**1500**	**2000**	**2500**	**3000**
CO2	0.7	1.1	1.39	1.72	2.2	2.5
CO	0.24	0.23	0.22	0.21	0.2	0.21
HC	200	194	184	183	180	177
NOx	129	131	142	150	158	165

Table 9. Experimental engine emissions result from the D95 fuel sample

Emissions (ppm)	Load (g)					
	500	**1000**	**1500**	**2000**	**2500**	**3000**
CO2	0.6	0.6	1.37	1.64	1.86	1.98
CO	0.22	0.22	0.2	0.19	0.18	0.19
HC	196	196	182	179	176	174
NOx	125	125	140	148	155	163

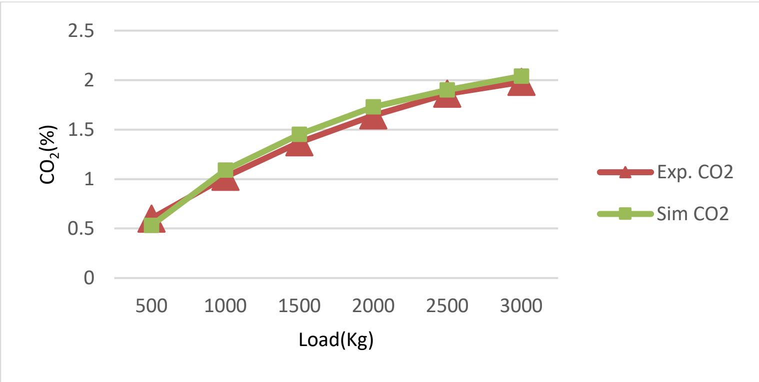

Fig. 6. Variation of carbon dioxide with load increase for D95 fuel samples

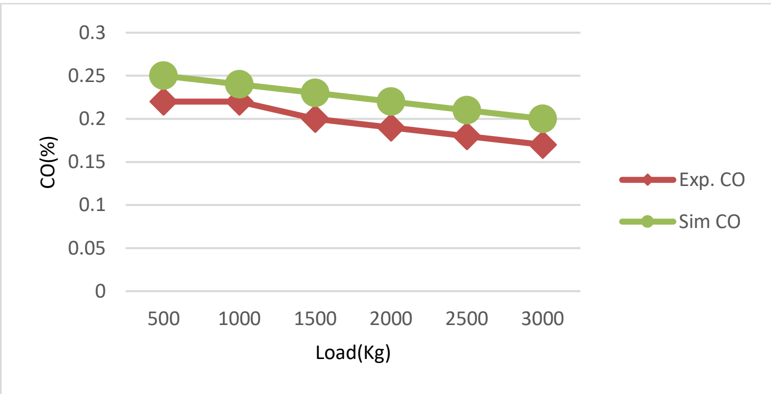

Fig. 7. Variation of carbon monoxide with load increase for D95 fuel samples

In Tables 8 -9, and Fig 8, unburnt HC emissions decrease with engine speed for both D100 and D95, but the decrease is more pronounced for the D95 fuel sample across all engine speeds. This trend can also be explained by the shorter chain length of butanol in the fuel mixture. The comparative analysis of experimental and simulated HC emissions for the D95 fuel sample suggests that at 500g, 1000g, 1500g, 2000g, 2500g, 3000g, and a constant speed of 1500 rpm, the simulated HC emissions are higher by 2.04%, 1.57%, 4.4%, 5.03%, 5.68%, and 5.75% than the experimental HC emissions results, respectively.

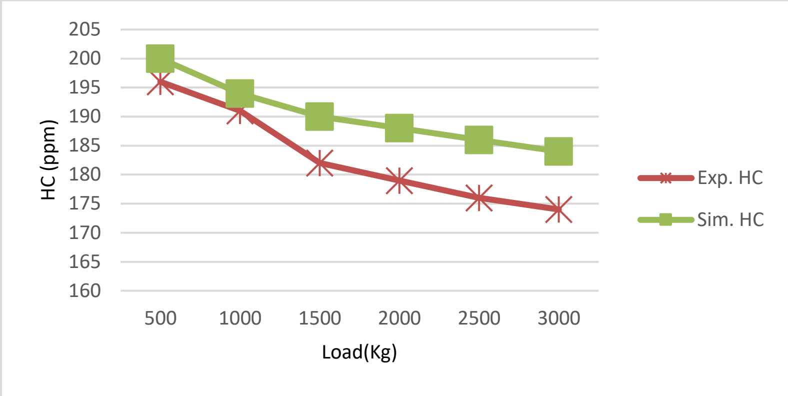

Fig. 8. Variation of unburnt HC emission with load increase for D95 fuel samples

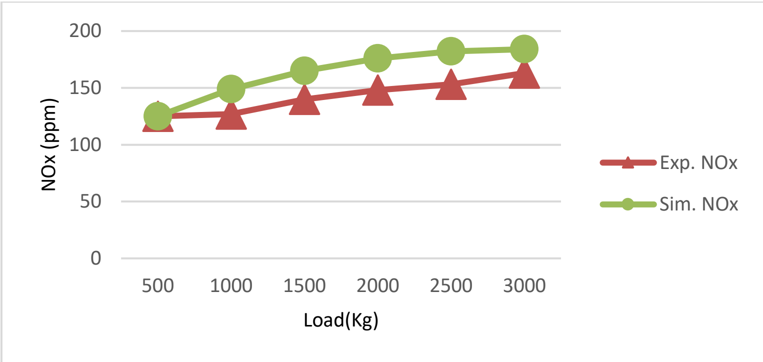

Fig. 9. Variation of NOx emission with load increase for D95 fuel samples

Lastly, Tables 8 and 9 that NOx emission levels for D100 and D95 increase with engine speed, but the level is lower for the D95 fuel sample across all engine speeds. In addition, Fig. 9 exhibited a comparative trend for experimental and simulated NOx emissions of the D95 sample at 500g, 1000g, 1500g, 2000g, 2500g, 3000g, at a constant engine speed of 1500 rpm, presented the simulated NOx emissions in a manner that is 0%, 17.32%, 17.86%, 18.91%, 18.95%, and 12.88% higher than the experimental NOx emissions levels.

Higher levels of NOx emissions in CI engines are primarily attributed to the combustion process and fuel characteristics. Factors such as elevated combustion temperature, lean fuel-air mixture, longer ignition delay, higher oxygen concentration, and fuel properties, including cetane numbers and sulfur content, contribute to increased NOx formation and this is implied by the relatively higher cetane number, longer ignition delay and oxygenation tendencies of butanol in the fuel mixtures [47-51].

The differences between the experimental and simulated outcomes, ranging from 0.12% to 12.88% across different engine loading conditions, can be attributed to various factors. These factors include limitations in the simulation model, such as its inability to fully replicate real-world engine behaviour, uncertainties in the input parameters, the impact of measurement inaccuracies or variations in the experimental setup, and variables like engine wear and manufacturing inconsistencies.

4. CONCLUSION

The experimental and simulation results provide insights into the effects of n-butanol-diesel fuel blends on engine performance, fuel economy, combustion characteristics, and emissions, and the following inference can be made from the study:

i. As engine load increases, simulated torque consistently surpasses experimental torque, suggesting the potential for enhanced power output and efficiency when using n-butanol blends.
ii. The D95 blend exhibits brake power comparable to that of traditional diesel

fuel, positioning it as a promising alternative for replacing conventional fossil fuels.

iii. Lower n-butanol blends display reduced engine performance, underscoring the importance of carefully considering the blend ratio for optimal outcomes.

iv. Blended fuels, particularly D95, contribute to improved fuel efficiency, resulting in reduced overall fuel consumption.

v. The addition of n-butanol to the fuel mixture enhances combustion behaviour and decreases the emission of harmful pollutants such as CO2, CO, unburnt HC, and NOx.

vi. These findings underscore the potential of n-butanol-diesel blends as sustainable and environmentally friendly options for transportation fuels.

vii. This research provides essential insights for policymakers, researchers, and industries striving for a cleaner and more sustainable future in the automotive sector.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Han X, Liu Z, Li X, Tian X, Zhang J, Wang Y. Combustion and emission characteristics of a diesel/n-butanol blend in a multi-cylinder compression ignition engine. Fuel. 2019;250:427-437.
2. Zhang R, Li H, Yao M, Zhang Y. Experimental study of combustion and emission characteristics of n-butanol/diesel fuel blend in a diesel engine. Fuel. 2017;209:739-746.
3. Joy N, Yuvarajan D, Beemkumar N. Performance evaluation and emission characteristics of diesel ignition enhancer blend propelled in a research diesel engine. International Journal of Green Energy. 2019;16(4):277–83. DOI:10.1080/15435075.2018.1561455
4. Lapuerta M, Armas O, Rodríguez-Fernández J. One global strategy to address the challenges posed by harmful emissions and the depletion of fossil fuels is the substitution of renewable fuels. Energy Conversion and Management. 2018;176:533-537.
5. Yuvarajan D, Venkata Ramanan M, Christopher Selvam D. Performance analysis on mustard oil methyl ester as a potential alternative fuel. Indian Journal of Science and Technology. 2016;9(37). DOI: 10.17485/ijst/2016/v9i37/101982.
6. Appavu P. Effect of injection timing on performance and emission characteristics of palm biodiesel and diesel blends. Journal of Oil Palm Research. 2018;30:674–81. DOI:10.21894/jopr.2018.0057.
7. Aden A, Ruth M, Ibsen K, Jechura J, Neeves K, Sheehan J, Wallace B, Montague L, Slayton A, Lukas J. Lignocellulosic Biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. NREL/TP-510-32438. National Renewable Energy Laboratory; 2002.
8. Valentin L, Grumezescu AM. (Eds.). Butanol: Industrial applications, biotechnology, and future perspectives. Elsevier; 2015.
9. Osman M et al. Conversion of butanol isomers via guaiacol on platinum/gamma-alumina catalysts. Catalysis Today. 2016;278:242-248.
10. Tsyganenko AA et al. Study of the effects of the structure of 1-butanol, 2-butanol, and isobutanol on the efficiency of their extraction from dilute aqueous solutions by isobutylene. Russian Journal of Physical Chemistry A. 2017;91(7):1395-1399.
11. Gao D et al. Selective Dehydrogenation of n-Butanol to Butyraldehyde over Copper-Based Catalysts. ACS Catalysis. 2018;8(3):2221-2231.
12. Hashemi MM et al. Estimation of volumetric properties for n-butanol + hydrocarbons binary mixtures using COSMO-SAC model. Journal of Chemical & Engineering Data. 2019;64(2):867-879.
13. Lamani VT, Yadav AK, Kumar GN. Effect of exhaust gas recirculation rate on performance, emission and combustion characteristics of common rail diesel

engine fuelled with n-butanol-diesel blends. Biofuel; 2017. Available:http://dx.doi.org/10.1080/17597269. 1369631.
14. Tashiro Y, Shinto H, Hayashi M, Baba SI, Kobayashi G, Sonomoto K. Novel high-efficient butanol production from butyrate by non-growing clostridium saccharoperbutylacetonicum n1-4 (at 13564) with methyl viologen. Journal of Bioscience and Bioengineering. 2007;104(3):238—240.
15. Ahmed A et al. Butanol as an alternative fuel for CI engine: A comprehensive review. Renewable and Sustainable Energy Reviews. 2015;51:1313-1328.
16. Paykani A et al. Comparative study on the effect of diesel, n-butanol, and biodiesel fuels on combustion and emission characteristics in a DI diesel engine. Fuel. 2016;165:157-166.
17. Bari S. Performance, Combustion and emission analysis of diesel engine fuelled with n-butanol biodiesel blends. International Journal of Vehicle Structures and Systems. 2017;9(2):84-89.
18. Pirouzpanah V et al. Experimental investigation on the performance and emission characteristics of a diesel engine fueled with n-butanol/diesel fuel blends. Fuel. 2018;233:205-215.
19. Jahanian O et al. Investigation of combustion, performance, and emission characteristics of a diesel engine using n-butanol-diesel blends. Energy & Fuels. 2019;33(8):7645-7656.
20. Kumar S, Cho JH, Park J, Moon I. Advances in diesel–alcohol blends and their effects on the performance and emissions of diesel engines. Renewable and Sustainable Energy Reviews, 22, 46–72. Available:https://doi.org/10.1016/j.rser.2013.01.017
21. Chen Z, Wu Z, Liu J, Lee C. Combustion and emissions characteristics of high n-butanol/diesel ratio blend in a heavy-duty diesel engine and EGR impact. Energy Conversion and Management. 2014;78:787-795.
22. Sendilvelan S, Rajan K. Effect of butanol-diesel blends in a compression ignition engine to reduce emission. Rasayan Journal of Chemistry (India). Computational Fluid Dynamics. 2017; 10(1):190-194.
23. Jamrozik A, Tutak W, Grab-Rogaliński K. Combustion stability, performance and emission characteristics of a CI engine fueled with diesel/n-butanol blends. Energies. 2021;14(10):2817.
24. Karagöz M. Investigation of performance and emission characteristics of an CI engine fuelled with diesel–waste tire oil–butanol blends. Fuel. 2020;282:118872.
25. Nayyar A, Sharma D, Soni SL, Mathur A. Experimental investigation of performance and emissions of a VCR diesel engine fuelled with n-butanol diesel blends under varying engine parameters. Environmental Science and Pollution Research. 2017;24:20315-20329.
26. Thakkar K, Kachhwaha SS, Kodgire P, Srinivasan S. Combustion investigation of ternary blend mixture of biodiesel/n-butanol/diesel: CI engine performance and emission control. Renewable and Sustainable Energy Reviews. 2021;137:110468.
27. Kumar N, Pali HS. Effects of n-butanol blending with Jatropha methyl esters on compression ignition engine. Arabian Journal for Science and Engineering. 2016;41(11):4327-4336.
28. Tutak W, Jamrozik A, Grab-Rogaliński K. Evaluation of combustion stability and exhaust emissions of a stationary compression ignition engine powered by diesel/n-butanol and RME Biodiesel/n-Butanol Blends. Energies. 2023;16(4):1717.
29. Li J, Hong G, Luo L, An X. Combustion and emission characteristics of diesel/n-butanol blends in a heavy-duty diesel engine: A CFD study. Energy Conversion and Management. 2019;186: 180-190
30. Sengupta A, Biswas S, Banerjee R. Performance-emission effect of n-butanol in reactivity controlled compression ignition regimes of biodiesel combustion. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 2023;45(4):11122-11141.
31. Zhang Z, Tian J, Li J, Lv J, Wang S, Zhong Y, Tan D. Investigation on combustion, performance and emission characteristics of a diesel engine fueled with diesel/alcohol/n-butanol blended fuels. Fuel. 2022;320:123975.
32. Li J, Zhang Z, Ye Y, Li W, Yuan T, Wang H, Zhang C. Effects of different injection timing on the performance, combustion and emission characteristics of

diesel/ethanol/n-butanol blended diesel engine based on multi-objective optimization theory. Energy. 2022;260:125056.
33. Zhang Z, Tian J, Xie G, Li J, Xu W, Jiang F, Tan D. Investigation on the combustion and emission characteristics of diesel engine fueled with diesel/methanol/n-butanol blends. Fuel . 2022;314:123088.
34. Solventis. N-Butanol Product. Online publication of Solventis, Compton House, The Guildway, Old Portsmouth Road, Guildford, Surrey, GU3 1LR, UK.21; 2022. Available:https://www.solventis.net/products/alcohols/n-butanol/.
35. NJDH. Right to Know: Hazardous Substance Fact Sheet. New Jersey, U.S.A; 2008. Available:http://www.nj.gov/health/eoh/rtkweb
36. SAE International. SAE J1349: Engine Power Test Code - Spark Ignition and Compression Ignition - Net Power Rating. Warrendale, PA: Society of Automotive Engineers (SAE); 2011.
37. International Organization for Standardization (ISO). ISO 8178: Reciprocating Internal Combustion Engines - Exhaust Emission Measurement - Part 1: Test-bed Measurement of Gaseous and Particulate Exhaust Emissions. Geneva, Switzerland: ISO; 2017.
38. ASTM International. (n.d.). ASTM D975-20: Standard Specification for Diesel Fuel. Available:https://www.astm.org/Standards/D975.htm
39. TQ. TD110-TD115 Test Bed and Instrumentation Manual for Small Engines,TQ Educational and Training Publishers, London. 2000;1-6.
40. GT-SUITE. GT-SUITE Engine Performance Tutorials VERSION 7.3. Gamma Technologies, Inc; 2012. Available:https://www.gtisoft.com/
41. Elfasakhany A. Experimental study of dual n-butanol and iso-butanol additive on SI Engine Performance and emissions. Fuel. 2016;163:166-174.
42. Grabys J. Influence of composition of gasoline-ethanol blend parameters of internal combustion engines, Journal of Kones, Internal Combustion Engines. 2012;10:3-4.
43. Kuszewski H. Physical and chemical properties of n-butanol–diesel fuel blends. Journal of Energy Fuels; 2018. DOI: 10.1021/acs. Energy fuels.8b02912 Downloaded from Available:http://pubs.acs.org
44. Agarwal AK. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. Progress in Energy and Combustion Science. 2007;33:233–271.
45. Szwaja S, Naber JD. Combustion of n-butanol in a spark-ignition IC engine. Fuel. 2010;89(7): 1573-1582.
46. Singh P, Singh A. Production of liquid biofuels from renewable sources. Progress in Energy and Com- Bustion Science. 2011;37:52–68. Available:https://doi.org/10.1016/j.pecs.2010.01.003
47. Heywood JB. Internal Combustion Engine Fundamentals. New York: McGraw-Hill; 1988.
48. Stone R. Introduction to Internal Combustion Engines. Macmillan International Higher Education; 2007
49. Ganesan V. Internal Combustion Engines. Tata McGraw-Hill Education; 1999.
50. Watson N, Janota M. Automotive Engine Valves. SAE International; 2002.
51. Ferguson CR, Kirkpatrick AT. Internal Combustion Engines: Applied Thermosciences. John Wiley & Sons; 2001.

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