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Use of butanol, pentanol and diesel in a compression ignition engine: A review

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Abstract

Using oxygenated alternative fuels in compression ignition (CI) engines is feasible for energy security problems and climate change. Alcohols are regarded as alternative fuels for compression ignition engines because of their excellent physicochemical features, emission, and combustion characteristics. Research on alcohols and their additions has progressed significantly in recent years. Several researchers have examined the combined effect of higher alcohol with diesel and their impact and challenged that concentrations of higher alcohol reduce harmful particulate emissions in CI engines. This paper mainly focused on the performance and emissions properties of higher alcohols like butanol and pentanol. Alcohol has a low energy content, typically affecting engine brake-specific fuel consumption (BSFC). Low-temperature combustion (LTC) in compression ignition engines can lower NO_x and smoke emissions, and improve the efficiency of the engine. LTC is done by combining higher alcohol with increased exhaust gas recirculation (EGR) rate and retarded fuel injection timing. The higher alcohol, along with the oxygen in the fuel reduces exhaust fumes, improves the air/fuel mixture by providing a longer ignition delay (ID), and can replace the fossil fuel like diesel (partially or whole) to allow efficient and clean combustion in CI engines. Finally, several significant findings and comments are provided regarding potential avenues for experimental research and future development. According to thorough analysis, bio-alcohols are considered to be a substitute fuel for CI engines.

Keywords: Diesel engines, Higher alcohol, Diesel, Butanol, Pentanol

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1. Introduction

The application of alternative fuels in the transportation and power-generating industries used in compression ignition (CI) engines is becoming increasingly significant [1]. This requirement becomes necessary because of two issues: decreased oil reserves, price instability, and emission regulations for human health and environmental preservation [2].

The petroleum industry is a crucial sector of the Indian economy, accounting for about 25% of the country's total energy consumption. However, India remains heavily reliant on imports to meet its domestic demand for crude oil, with nearly 80% of its crude oil requirements being imported [3]. India's oil demand is projected to rise from the current 4.7 million barrels per day (mb/d) to 6.7 mb/d in 2030 and 8.3 mb/d in 2050 [4]. Despite the high efficiency of CI engines, the primary pollutants emitted from diesel fuel are HC, NO_x, and CO [5].

Nomenclature

ABE	– acetone-*n*-butanol-ethanol
ABED	– ABE/diesel blends
BSFC	– brake-specific fuel consumption
BTE	– brake thermal efficiency
CI	– compression-ignition
CN	– cetane number
CO	– carbon monoxide
CO_2	– carbon dioxide
CRDI	– common rail direct injection
CV	– calorific value
DI	– direct injection
EGR	– exhaust gas recirculation
HC	– hydrocarbon
HCCI	– homogeneous charge compression ignition
HRR	– heat-release-rate
LHE	– latent heat of evaporation
LHV	– lower heating value
LTC	– low-temperature combustion
NO_x	– nitrogen oxides
PODEn	– poly-oxy methylene dimethyl ethers
PPCI	– partially-premixed-compression-ignition
RCCI	– reactivity-controlled-compression-ignition
RSM	– response surface methodology
SCR	– selective catalytic reduction
HCOOH	– formic acid
HCHO	– formaldehyde

In recent years, various measures have been taken to reduce these exhaust gases from diesel engines by implementing regulations such as BS (brake-specific) standards, alternative fuels, etc. Among these measures, alternative biofuels have become essential because of the rising price of retrofitting CI (compression-ignition) engines, rising oil prices, and declining oil reserves [6]. Due to their abundant sources and self-contained oxygen properties, oxygenated fuels are gaining much attention as new alternative fuels. Alcohol [7], ester [8], ether [9], and other alcohol-based fuels are currently the primary oxygenated alternative fuels. Numerous experiments have shown that blending these fuels with diesel reduces smoke opacity and increases the ambiguous interactions between NO_x and soot [10,11].

Different alcohols, like methanol and ethanol, are currently used as alternative biofuels, and higher alcohols, like butanol, pentanol, etc. can also be used as alternative fuels in CI engines. By using these alcohols with diesel in CI engines, the particulate emissions can be decreased. Moreover, a few issues exist while using lower alcohol in diesel engines. Previous researchers have found that lower alcohols, such as methanol and ethanol, have less miscibility in diesel and might cause phase separation problems at low temperatures due to their poor chemical and physical characteristics [12]. Also, low-carbon alcohols have low CN (cetane number), low viscosity, and high latent heat of evaporation (LHE), impacting engine performance and emissions [13–15]. To address these issues, various approaches can be employed, including alcohol fumigation, dual injection, blending alcohol with diesel fuel, and creating alcohol-diesel fuel emulsions [16].

A double injection system or alcohol fumigation can productively solve the miscibility problems of alcohol/diesel fuel blends. Ghadikolaei et al. [17] examined that fumigation might solve the miscibility problem in the alcohol-diesel blend. In addition, Liu et al. [18] discovered the various consequences of ethanol/PODEn/diesel fuel blends on CI engines. They found that PODEn enhanced the emission and combustion features of CI engines. Phase separation problems can be reduced by adding co-solvents or emulsifiers in lower alcohol/diesel blends [19]. Higher alcohols have drawn more attention because of their high cetane number, energy density, mixing stability, and reduced moisture absorption compared to lower alcohols. Higher alcohols contain more carbon, are less hygroscopic, and are less polar. The suitability of neat butanol for CI engines is constrained by several factors. Its lower cetane number, diminished energy density, elevated heat of vaporization, potential corrosiveness to engine components, and compatibility issues with seals and gaskets all pose challenges. Moreover, the limited availability and underdeveloped infrastructure for butanol distribution exacerbate its practicality as a transportation fuel for CI engines. These properties contribute to ignition delays, incomplete combustion, reduced efficiency, heightened emissions, and reliability concerns. Nonetheless, despite these limitations, the environmental benefits of butanol, such as lower emissions, suggest potential avenues for improvement through fuel blending or the adoption of advanced engine technologies [20]. Therefore, the combination of higher alcohols such as butanol, pentanol, etc. along with diesel without the addition of emulsifiers or co-solvents does not cause phase separation problems. Higher alcohols can be utilized as solvents for alcohols like methanol and ethanol [21]. Secondly, they are less corrosive in nature because of their lower hygroscopicity and lower water content [22]. These alcohols have longer carbon chains than lower alcohols, which increases their CV (calorific values), CN, and density. Higher alcohol concentrations can also extend the ignition delay period, improving the premixed and diffusion combustion phases and thoroughly mixing the air and fuel.

Biobutanol and biopentanol are biofuels produced via fermentation processes, but they differ in microorganisms and pathways. Biobutanol, often derived from acetone-butanol-ethanol (ABE) fermentation by Clostridium bacteria, utilizes various feedstocks like sugar cane and cellulose-rich biomass. The process involves hydrolysis to break down feedstock into fermentable sugars, fermentation by bacteria yielding butanol, acetone, and ethanol, and distillation to separate butanol. Conversely, biopentanol production may involve the genetic engineering of microorganisms for pentanol synthesis, with similar feedstock options. Challenges include optimizing microbial strains for high yields and reducing production costs to compete with traditional fuels. Both biofuels represent promising alternatives necessitating ongoing research and development [23].

Integrating an economic analysis into the assessment of higher alcohol fuels entails evaluating their cost of production, including raw materials, processing, and infrastructure, alongside feedstock availability and price fluctuations. Assessing energy content and engine efficiency relative to conventional fuels is essential, as is considering the cost of infrastructure modifications. Market demand, price sensitivity, environmental and social costs, policy support, and long-term technological advancements all play pivotal roles in determining the economic viability and potential societal benefits of adopting higher alcohol

Table 1. Physicochemical properties of fuels [16,22,48].

Properties	**Diesel**	**Methanol**	**Ethanol**	***n*-Butanol**	***n*-Pentanol**
Mol. formula	$C_{12}H_{26}$-$C_{14}H_{30}$	CH_3-OH	C_2H_5-OH	C_4H_9-OH	C_5H_{11}-OH
Mol. weight (kg/kmol)	191–210	31.84	45.88	75.12	87.85
Density (kg/m^3) at 15℃	838	790.73	790.2	810.1	815.2
Flashpoint (℃)	72	11.5–12.5	14.5	27	48
Boiling point (℃)	181–358	65.2	79.3	116.2	138.1
Cetane number (CN)	51.5	5.5	8.2	16	17.82–20
LHE (kJ/kg)	252–288	1160.73	919.37	582.24	309.15
Water solubility at 20℃ (%weight)	Immiscible	Miscible	Miscible	8.1	1.9
C (%weight)	85.83	38.18	51.84	65.22	67.83
O (%weight)	0.0	50.10	35.23	22.15	19.05
H (%weight)	14.20	13.24	12.92	13.54	14.21
C/H ratio	5.98	3.08	3.92	5.02	5.06
Self-ignition temperature (°C)	248–302	385	363	343	298
LHV (MJ/kg)	44.15	20.04	27.08	34.17	34.92
Vapour pressure (mmHg)	0.42	126.5	54.6	6.8	6.8
Saturation pressure (kPa) at 38℃	2.08	32.02	14.06	2.94	4.18
Lubricity (µm corrected wear scar)	314.8	1109.2	1056.5	592.10	677.15
Kinematic viscosity at 40℃ (mm/s^2)	3.45	0.52	0.98	2.56	2.83

fuels. Higher alcohols have lower total production costs than lower alcohols in terms of price. To control fuelling in internal combustion engines using either fossil fuel or biodiesel, various strategies are employed to optimize engine performance and emissions. Two primary approaches are commonly focused on: maintaining a constant initial injection angle or optimizing the combustion phasing, typically measured by the CA50 angle (the crank angle at which 50% of the fuel mass has burned) [24]. Research trends indicate that while maintaining a constant initial injection angle provides a useful baseline, optimizing the CA50 angle generally yields better efficiency, performance, and emissions outcomes. This optimization is especially critical for biodiesel due to its distinct combustion properties compared to fossil fuels. Consequently, modern engine control strategies often include CA50 optimization to adapt to varying fuel characteristics and operating conditions, ensuring optimal engine performance and reduced environmental impact.

Yanai et al. [25] examined the consequences of neat butanol and found that the performance and emission features of the engine are affected by the spray characteristics and advanced injection angle strategy. Gautam et al. [26] have also found that the CO emission decreased and BTE (brake thermal efficiency) increased with the advancement in injection angle. By using RSM (response surface methodology), Kumar et al. [27] observed the impact of different factors on CI engines and concluded that fuel injection pressure seriously influences the performance and emissions behaviour of CI engines. Low-temperature combustion (LTC) is a promising strategy for simultaneously reducing NO_x and smoke emissions while enhancing combustion efficiency. LTC is characterized by a well-prepared premixed fuel/air mixture that combusts at lower temperatures after an extended ignition delay. The most effective methods to achieve LTC include using exhaust gas recirculation (EGR) and delaying the injection timing. Combustion tests were conducted in an optically accessible diesel engine using a 20% butanol/diesel blend under varying injection timings and EGR rates. A partially premixed low-temperature combustion (LTC) was achieved with late injection timing combined with a high EGR rate of 50%. This resulted in significant reductions in smoke and NO_x emissions, with a minor decrease in efficiency [28].

For instance, RCCI (reactivity-controlled-compression-ignition) [29], PCCI (partially-premixed-compression-ignition) [30], and HCCI (homogeneous charge compression ignition) [31] have demonstrated the ability to achieve the most stringent emissions standards in the transportation sectors. Higher alcohol PFI (port fuel injection) and diesel DI (direct injection) can produce RCCI. The combustion phase may be more readily controlled, a more comprehensive operating range is attained, the efficiency of diesel engines is substantially improved, and extremely low NO_x and particulate matter emissions are maintained. However, because of its physicochemical characteristics, increasing alcohol consumption in compression ignition engines typically impacts the performance of the engines. While using higher alcohols in compression ignition engines, including nanoparticles [32] and polymethyl dimethyl ether [33] can also enhance the performance of the engines.

The primary goal of this study is to present a thorough analysis of higher alcohol and its impacts on CI engines' performance, combustion, and emissions. Numerous researchers and scientists have examined butanol and pentanol in various ratios with diesel to see whether or not they are suitable as fuel for the current diesel engines. The recent research and prior results about replacing (fully or partially) fossil fuel with these alcohols in compression ignition engines were usually successful since they increased the fuel's renewable fraction while reducing regulated emissions and improving efficiency.

2. Butanol as fuel in CI engine

Butanol, saturated hydrocarbon, is a straight-chain alcohol having 4-carbon atoms mainly extracted from fossil fuels and bio-derived substances. Despite this, both butanol and pentanol have similar physicochemical properties and give identical results when used in CI engines. Butanol can be added in significant proportion to diesel fuel and used; however, it is not suitable for the complete replacement of diesel directly in diesel engines due to the different properties than diesel (see Table 1). Butanol/diesel blends are one of several possibilities for making diesel engines suitable with alcohol. Due to the hydrophilic nature of methanol and ethanol, it does not form a proper mixture with diesel as they become separated into different liquid phases over several periods, and it gives undesirable effects while using them in diesel engines. Hence, it requires an additional co-solvent to attain a better blend with diesel. Butanol exhibits better miscibility characteristics with diesel blends because of its lower polarity [34]. No emulsifying agents are required for diesel/butanol blends as they do not undergo phase separation even after many days [35].

Moreover, it acts as a solvent for methanol/diesel fuel blends [36] and ethanol/diesel fuel blends [37–39] while used in CI engines. Although blending can be completed either splash-blended in the storage reservoir right before distribution or in-line at the terminal, a specific manufacturing facility is not required to handle the stable diesel/butanol fuel blend due to its ease of attainment [40]. Another significant benefit is that butanol may be blended into diesel at larger ratios, indicating that perhaps the fuel has a more substantial share of renewable energy. According to several studies, using butanol/diesel mixes, butanol can substitute up to 40% of diesel fuel without requiring significant changes to the current engine system [41].

The low heating value (LHV) of a fuel impacts the engine's power production. Because alcohol's heating value rises as carbon atoms increase, butanol has a higher heating value compared to lower alcohols like methanol and ethanol. However, butanol has a 23% lesser LHV than diesel; therefore, it requires a higher quantity of diesel-butanol blended fuels to obtain equal power output from the engine. As the number of carbon atoms grows, alcohol's volatility and auto-ignition temperature drop. Therefore, diesel/butanol mixtures do not impact the ignition issues at various low-load settings [42]. It lowers the CN of blends with diesel, reduces auto-ignition properties and lengthens ignition delay. Direct application of these higher alcohols in unmodified CI engines is prohibited for this very reason.

2.1. Combustion, performance and emission behaviour of butanol

An exhaustive research review on the effects of blending butanol with diesel in various kinds of CI engines is shown in Table 2.

2.2. Summary

According to the above literature review, adding butanol to diesel has various effects on the CI engine performance and emissions:

1. More butanol content in diesel/butanol blends lowers the fuel's CN, increases ignition delay (ID), and increases the maximum heat release rate (HRR).
2. The peak pressure inside the engine cylinder improves the premixed phase of combustion, increases BTE, reduces indicated torque, power and IMEP (indicated mean effective pressure), and increases CO and HC emissions.
3. Combustion temperatures of diesel/butanol blends are low at medium and low loads, and which also, due to the lower calorific value and higher LHE of butanol as compared to diesel, reduce NO_x emissions. Alternatively, increased NO_x emissions are caused by an extended premixed combustion phase due to the higher combustion temperatures at high loads.
4. Butanol increases combustion by increasing the distillation and viscosity of biodiesel/butanol blends, increasing the BTE and decreasing soot particles, CO, and unburnt hydrocarbon emissions but lowering BSFC. Its higher distillation temperature, in comparison to ethanol, aids in superior fuel vaporization, thereby enhancing the combustion process.
5. When PODEn is added to diesel blend (DB), it increases the CN, which decreases the delay period while increasing HC, NO_x, and exhaust emissions while reducing soot emissions. Reducing the time intervals between the pilot and direct injections can help lower hydrocarbons and carbon monoxide emissions.

Adding butanol to biodiesel improves the BTE and increases BSFC while reducing ID period, cylinder pressure, maximum HRR, and NO_x, HC, and CO emissions. Simultaneously, the current research also suggests that ABE has a high potential for reducing butanol recovery costs and lowering soot and NO_x emissions.

Oxygen in fuel affects combustion and emissions, promoting complete oxidation and reducing CO and hydrocarbon emissions while potentially increasing NO_x. It also influences soot and particulate matter formation, favouring smaller particles in oxygen-rich environments [43]. Understanding oxygen's role is crucial for emission control strategies, offering opportunities to mitigate emissions. Balancing oxygen content is essential for efficient combustion with minimal environmental impact, enhancing sustainability in combustion-related activities for cleaner air and improved environmental health.

The mixed results observed in studies on using higher alcohols as fuel in diesel engines – where some parameters increase in some studies and decrease in others – can be attributed to factors such as variations in fuel composition, engine types, measurement techniques, environmental conditions, and data analysis methods. Addressing these factors can help researchers reach more definitive conclusions about the use of higher alcohols in diesel engines, potentially leading to optimized formulations and enhanced performance and emissions profiles. Additionally, several studies indicated that combining higher alcohols with nanoparticles might enhance engine performance by boosting combustion and reducing emissions.

3. Pentanol as fuel in CI engine

Pentanol is also a saturated higher alcohol with 5-carbon atoms having a higher CN, a higher energy density, a more stable pentanol-diesel blend, and a less moisture-absorbing tendency than other lower alcohols. Pentanol is more similar to diesel fuel in comparison to other alcohols in terms of its latent heat of vaporisation, viscosity, and density. It can be manufactured using biological processes such as biosynthesis of glucose using bacteria (Escherichia coli) and natural fermentation using engineered microorganisms [44]. Pentanol is a fantastic sustainable fuel for CI engines.

Table 2. An overview of studies of blended butanol/diesel fuels in various types of compression ignition engines.

Ref.	Engine	Fuels used	Test conditions/ variables	Blend designation	Performance		NOx	Soot	HC	CO
					BSFC	BTE				
[49]	4-cylinders, 16-valve	Diesel + *n*-butanol	2000 rpm, 4000 rpm	20% NB	↑	↑	↑		↓	↑
				30% NB	↑	↑	↑		↓	↑
				40% NB	↑	↑	↑		↑	↑
[50]	4-stroke, 1-cylinder	Diesel + butanol isomers	3000 rpm	10% NB	↑	↑				
[51]	4-stroke, 1-cylinder	Diesel + butanol isomers	2000 rpm	8%, 16%, 24% NB			↓	↓		
[52]	4-stroke, 4-cylinder, 4-valve, VGT	Diesel + butanol isomers	1400 rpm	50% NB	↑		↑	↓	↑	↑
				50% IB	↑		↑	↓	↑↑	↑
				50% SB	↑		↑	↓	↑↑	↑↑
				50% TB	↑		↑	↓	↑↑	↑
[53]	4-stroke, 4-cylinder, DI	Diesel + methanol + *n*-butanol	2000 rpm	10%, 15% NB			↓	↓	↓	↓
[54]	4-cylinder, DI	Diesel + ethanol + *n*-butanol	1600 rpm	5 %, 10 %, 13 %, and 18 %NB	↑	↑	↓ LL ↑ HL	↓		↓
[55]	4-cylinders, 16 valves	Diesel + *n*-butanol + PODEn	Injection strategy 1600 rpm	20% NB 20% PODEn			↑	↓		↓
[56]	4-stroke, 2-cylinder, CRDI engine	Diesel + butanol + DEE	1600 rpm	85% diesel 15% NB doped with 0.3% DEE	↓	↑	↓			↓
[57]	4-stroke, 4-cylinder	Diesel + butanol	1800 rpm	80% diesel, 20% NB			↓		↑	↑
[58]	4-stroke, 1-cylinder, diesel engine	Diesel, mango seed, butanol	1500 rpm	75% diesel 20% MS 0%, 5%, 10%, and 15% butanol	↓	↑	↓		↓	↓
[59]	4-stroke, 1-cylinder	Diesel +ABE	1200 rpm	80 % diesel, 20 %ABE			↓	↑	↑	↑
[60]	4-stroke, 1-cylinder, DI, diesel engine	Diesel + alcohol + Al_2O_3 nanoparticles	1200 rpm	84% diesel, 16% *n*-butanol doped with Al_2O_3 nanoparticles			↑	↑ LL ↓ HL	↓	↓

Note: ↑↑ means increased substantially by, / – not changed significantly by, ↓ – decreased by, ↑ – increased by, NB – *n*-butanol, TB – *tert*-butanol, IB – isobutanol, DEE – diethyl ether, MS – mango seed, SB – *sec*-butanol, ABE – acetone–butanol–ethanol, VGT – variable geometry turbocharger, LL – low-load, HL – high-load.

Even after long days, pentanol diesel blend fuel exhibits improved blend stability without phase separation [45]. Pentanol and diesel have comparable viscosities; however, pentanol/diesel mixtures often have a lower density than pure diesel fuel. Pentanol/diesel blends could help to achieve better atomization and combustion of fuels in CI engines. Pentanol/diesel mixes have flashpoints exceeding 37.8°C, making them inflammable from a safety perspective. The CFPP (cold filter plugging point) behaviour of pentanol/diesel blends are below the limit as per EN 116 standards [46].

3.1 Combustion, performance and emission behaviour of pentanol

An exhaustive research review on the effects of blending pentanol along with diesel in various kinds of CI engines is shown in Table 3.

Table 3. An overview of studies on using blended pentanol/diesel fuels in various types of compression ignition engines (for legend see Table 2).

Ref.	**Engine**	**Fuels used**	**Test conditions/ variables**	**Blend designation**	**Performance**		**NO_x**	**Soot**	**HC**	**CO**
					BSFC	**BTE**				
[61]	1-cylinder	Diesel + *n*-pentanol	1500 rpm,		↑	↓	↓ LL ↑ HL		↑	↑
[62]	4-cylinder	Diesel + pentanol		Diesel/n-pentanol blends				↑		↑
[63]	4-stroke, 1-cylinder, DI	Diesel + pentanol	1500 rpm	Diesel/n-pentanol blends	↑	↓			↑	↑
[64]	4-stroke, 1-cylinder, DI	Diesel + pentanol	3000 rpm	10% NP	↑	↓				
[65]	1-cylinder diesel engine	1-pentanol/diesel blend	2000 rpm	10%, 20%, and 30%	↑	↓	↓	↓	↑	↑
[66]	4-stroke engine	Diesel-Jatropha-pentanol	1500 rpm	J20 D65 P15		↓	↑	↓	↓	↑
[67]	4-stroke, 4-cylinder, diesel engine	waste oil-derived biodiesel, diesel, and pentanol	1800 rpm indirect-injection	79.09% diesel, and 12.58% 1-pentanol 8.33% WOB	↑	↓	↓		↓	↓
[68]	4-stroke, 1-cylinder, diesel engine	Diesel–mahua methyl ester–pentanol	20 MPa to 50 MPa 2000 rpm	70% diesel 10% pentanol, and 20% MME biodiesel	↓	↑		↓	↓	↓
[69]	4 stroke, 1-cylinder	Diesel + biodiesel + pentanol		BD70 P30			↑		↓	↓
[66]	4-stroke 1-cylinder diesel engine	Diesel, Jatropha, biodiesel, and pentanol	1500 rpm	10%, 15% pentanol		↑	↑	↓	↓	↑

Note: WOB – waste oil-derived biodiesel, MME – mahua methyl ester, BD – diesel +biodiesel, P – pentanol.

3.2. Summary

According to the above literature review, adding pentanol to diesel has different effects on CI engine performance and emissions:

1. Pentanol-diesel blended up to 45% v/v can be used in CI engines without any modification or damage.
2. Pentanol-diesel blended up to 45% v/v can be used in CI engines without any modification or damage.
3. Several researchers conducted chemical modelling studies and kinetic tests to examine the principles of *n*-pentanol to employ pentanol as a next-generation biofuel. Data on oxidation, laminar flame velocity, reactivity flame instability, ignition delay time, species, and concentration are all included in the combustion modelling.
4. As the content of pentanol increases, the ID period increases due to the low CN of the pentanol/diesel blend fuel. Unlike diesel, higher peak cylinder pressures and higher premix HRRs are reported for pentanol-diesel blends.
5. Because of their lower viscosity and high oxygen concentration, pentanol/diesel blends enhance the performance of atomization and combustion compared to diesel. Generally, it offers much better thermal efficiency than other alcohols. However, the pentanol/diesel mixture slightly increases the engine's BSFC, so more fuel is required for the same performance.

The increased combustion temperature and oxygen content increase the NO_x emissions at very high loads while using pentanol/diesel blends as fuel. Pentanol/diesel blends have a lower cetane number due to the higher LHV of pentanol. Due to their increasing oxidizing properties, soot emissions decrease with increasing the pentanol content in diesel/pentanol blends. In CI engines, pentanol typically exhibits superior combustion, performance and emissions characteristics. Pentanol and its additives, like cetane number modifiers and nanoparticles, can simultaneously improve efficiency and reduce emissions in advanced combustion. Using pentanol in engines minimizes fossil fuel needs and reduces environmental pollution.

First-generation biofuels are derived from edible crops such as corn and sugarcane. Second-generation biofuels use non-edible sources, including plant materials like wood, agricultural residues, and municipal solid waste. Third-generation biofuels primarily come from algae and can also utilize carbon dioxide (CO_2) as a feedstock [47]. Oxygenated fuels and paraffinic fuels each have unique benefits and drawbacks. Oxygenated fuels are effective in lowering emissions and making use of renewable resources, although they struggle with lower energy density and compatibility issues. On the other hand, paraffinic fuels offer high energy density and clean combustion, but they are more expensive to produce and less widely available. The decision to use one type of fuel over the other depends on the specific application, existing infrastructure, and environmental objectives.

4. Conclusions

Butanol and pentanol are second/third-generation biofuels made from lignocellulosic biomass in environmentally friendly ways that do not rely heavily on food crops. They are similar to traditional biofuels in that they can address environmental degradation and energy insecurity. The following findings have been derived from this thorough study of the applications of higher alcohols in CI engines:

- Compared to diesel, higher alcohol/diesel blends have higher premixed heat release rates and peak cylinder pressures. Brake thermal efficiency of engines is improved by applying higher alcohols such as butanol due to low cetane number. It also enhances the quality of fuel atomization as the mixture becomes less viscous and denser.
- The oxygenated nature of higher alcohols typically results in a reduction in particulate emissions. The use of pentanol in diesel engines reduces brake thermal efficiency.
- Increasing the amount of butanol in the butanol/diesel blend generally decreases NO_x emissions. However, at high loads, for pentanol-containing alcohol NO_x, emissions rise linearly with their content. Generally, higher alcohol levels lead to a rise in CO and HC emissions. For engines running on higher alcohol levels, EGR is the most common technique to reduce NO_x emissions, followed by delayed injection.
- Diesel/higher alcohols blended fuel that contains PODEn, or CN modifiers, increases the CN, shortens the ID, and reduces soot particles and CO emissions. Nanoparticles enhance the combustion chamber's superior mixing capability with fine atomization; due to this, their use improves engine brake thermal efficiency and reduces brake-specific fuel consumption. It has been discovered that the application of higher alcohols as well as nanoparticles can improve engine performance and lower its emissions.

The impact of butanol and pentanol blended with diesel is more significant on CI engine performance and emissions and requires further investigation at high altitudes and under time-dependent (transient) conditions such as changes in load, acceleration, and transient or rotary drive cycles. Furthermore, the study is necessary to apply higher alcohol levels in compression ignition engines, optimize combustion characteristics, and specify optimum blend fuel ratios for the stability and long-term durability of the engines.

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