ETHANOL-DIESEL AND BIODIESEL BLENDS: ENHANCING DIESEL ENGINE EFFICIENCY AND REDUCING EMISSIONS- A REVIEW

AMESTECURI ETANOL-DIESEL ȘI BIODIESEL: ÎMBUNĂTĂȚIREA EFICIENȚEI MOTOARELOR DIESEL ȘI REDUCEREA EMISIILOR - O ANALIZĂ

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***Abstract**: This research explores using ethanol, biodiesel, and diesel blends in compression ignition engines to enhance efficiency and reduce environmental impact. It examines the effects of fuel composition on combustion properties, engine performance, and emissions. Findings indicate that while ethanol can improve combustion, it may reduce power output and increase emissions of pollutants like HC and NO_x. The study highlights the complexity of optimising fuel blends influenced by engine parameters and injection conditions. Despite challenges, blends show promise in reducing emissions like CO and PM, offering cleaner alternatives for diesel engines and aiding in environmental conservation.*

Keywords: Diesel engine; Diesel-biodiesel-ethanol blends; Combustion; Engine performance; Exhaust emissions.

***Rezumat**: Această lucrare analizează utilizarea etanolului, biodieselului și amestecurilor diesel în motoarele cu aprindere prin compresie pentru a spori eficiența și a reduce impactul asupra mediului. Se examinează efectele compoziției combustibilului asupra proprietăților de combustie, performanței motorului și emisiilor. Rezultatele indică faptul că, în timp ce etanolul poate îmbunătăți arderea, poate reduce producția de energie și poate crește emisiile de poluanți precum HC și NO_x. Studiul evidențiază complexitatea optimizării amestecurilor de combustibil, influențată de parametrii motorului și de condițiile de injectare. În ciuda provocărilor, amestecurile sunt*

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promițătoare în reducerea emisiilor, cum ar fi CO și PM, oferind alternative mai curate pentru motoarele diesel și ajutând la conservarea mediului.

Cuvinte cheie: Motor diesel; Amestecuri diesel-biodiesel-etanol; Combustie; Performanța motorului; Emisii de eșapament.

Nomenclature

BP	Brake power	DI	Direct injection
BSFC	Brake-specific fuel consumption	EoC	End of combustion
BTE	Brake thermal efficiency	EGR	Exhaust gas recirculation
CD	Combustion delay	EGT	Exhaust gas temperature
CN	Cetane Number	HC	Hydrocarbons
CO	Carbon monoxide	HRR	Heat release rate
CO_2	Carbon dioxide	ID	Ignition delay
CV	Calorific value	MFB	Mass of fuel burned
CRDI	Common rail direct injection	NOx	Nitrogen oxide
CV	Calorific value	PM	Particulate Matter
D100	100% diesel	SoC	Start of combustion
Symbols			
B, BD	*Biodiesel*	*E*	*Ethanol*
D	*Diesel*	*M*	*Methanol*
DBE	*Diesel-biodiesel-ethanol*		

1. Introduction

An enormous transformation is taking place in the world's energy landscape due to climate change mitigation, environmental sustainability, and energy security worries.

The CI engine plays a significant role in many industries, including transportation, manufacturing, and power production, due to their dependability, sturdiness, and high energy density, which makes them crucial for supplying power to key areas of the global economy [1-3]. However, due to the difficulties that come with diesel engines naturally, such as the emissions of nitrogen oxides (NOx), PM and greenhouse gases (GHGs), there is a greater need than ever for creative solutions that will improve their performance while reducing their impact on the environment [4-6]. The search for more sustainable energy sources has sparked a boom in interest in alternative fuels and additives that can increase combustion efficiency, lower emissions, and reduce harmful pollutants.

Several countries have recently moved toward alternative options for fossil fuels, fearing that dependence too heavily on fossil fuels will risk their growth path. The first choice of researcher is biofuels, which are classified as renewable energy sources as it is obtained from biomass. Also, the growth of strong biofuel production chains may increase a country's energy independence.

In this situation, biodiesel, a kind of biofuel with characteristics resembling those of conventional fossil diesel, may readily replace traditional fossil diesel in blends with little to no engine adjustments [7-9]. It enables a large decrease in CO and PM emissions. The primary difference between biodiesel and normal diesel is its reduced calorific value; it has 36–40 MJ/kg of ethyl ester of fatty acid as compared to 42–44 MJ/kg for regular diesel [10]. As a result, BSFC is higher than it would be for ordinary diesel. However, as biodiesel is not yet completely capable of meeting the criteria for replacing fossil diesel, ethanol can be set up as a complementary alternative biofuel in diesel engines.

The utilisation of ethanol as an alternative fuel for diesel engines, alongside biodiesel, has gained recognition in recent years [11, 12]. Ethanol offers the potential to enhance engine performance and decrease emissions. However, its use in CI engines presents challenges due to its poor miscibility low CN with diesel at lower temperatures, and other characteristics such as reduced heating value, viscosity, and lubricity [13-16]. Despite these challenges, ethanol's application in CI engines has expanded due to several developments: ethanol fumigation, where ethanol is introduced into the intake air charge; dual fuel direct injection, involving separate injections of each fuel; and blends of diesel and ethanol, where the fuels are combined before injection [17, 18]. Notably, the simplicity of the ethanol/diesel blend technique is significant, allowing CI engines to operate on ethanol without requiring further technological modifications. Studies comparing ethanol-diesel blends to pure diesel fuel have shown higher BTE and lower BSFC. Although there is a slight decrease in engine power, there is a substantial reduction in exhaust emissions [19-21]. An interesting observation when ethanol and diesel are combined is the fuel ignition delay (ID), caused by higher heat of vaporisation of ethanol (around 903 kJ/kg for anhydrous ethanol) compared to diesel fuels (approximately 250 kJ/kg) [22]. Furthermore, the presence of ethanol leads to significant heat withdrawal from the air-fuel charge during evaporation, lowering the temperature inside the cylinder, preventing favourable auto-ignition conditions, and ultimately delaying the initial stages of combustion [23].

The ability of ethanol to mix with diesel is influenced by the composition of hydrocarbons and the wax concentration in the base diesel, as well as the ethanol concentration and temperature. When its content is less than 30% and the temperature is higher than 20°C, ethanol is highly soluble in diesel [24-26]. However, ethanol and diesel barely mix below 10°C, which affects the flow and filterability of ethanol-diesel mixtures. When these mixes are utilised without stability additives, this lack of miscibility might cause operating problems in compression ignition engines. To address this problem, two methods involve additives to ensure blend stability: one is adding surfactants (emulsifiers) to form stable micro-emulsions, and the other is adding co-solvents to create stable and uniform solutions. Biodiesel, due to its bipolar molecular structure, acts as an emulsifier, allowing diesel and biodiesel to mix in any proportion. Moreover, biodiesel has a strong affinity for ethanol, preventing phase separation between ethanol and diesel under normal conditions [27, 28].

The central theme of this work is to thoroughly study the utilization of DBE blends on diesel engines. These fuel scenarios have emerged as possible possibilities for addressing the issues that regular diesel fuel presents. To enhance the information and findings for the specified criteria for academics, policymakers, and others interested in biofuel, the literature evaluated in this study was compiled over the last 5 years from highly regarded journals in scientific indexes. This study attempts to provide insights that might guide future research paths and help the development of creative solutions for cleaner and more efficient diesel engine operation by evaluating their combustion characteristics, emissions consequences, and obstacles. As a result, it adds to the continuing discussion about sustainable energy and connects with worldwide efforts to create a healthy balance between energy requirements and environmental stewardship.

The importance of this study rests in its ability to bridge the gap between current energy demands and the need to safeguard the environment. As nations throughout the world attempt to meet aggressive emissions reduction objectives and transition to low-carbon economies, the use of alternative fuels and sophisticated combustion methods becomes increasingly important. The review's findings have consequences for industry, governments, and academics since they guide methods for optimising diesel engine performance and contributing to a sustainable energy future.

2. Properties of blends

2.1. Physicochemical properties of diesel, biodiesel, and ethanol

Biodiesel, a renewable energy source, has attracted considerable attention from scientists and researchers worldwide as a potential alternative fuel. Different countries produce biodiesel using various raw materials based on geography and climate. For example, the United States utilizes soybean oil, the Philippines uses coconut oil, Europe relies on sunflower oil, and

Southeast Asia produces palm oil [29]. Biodiesel can be derived from vegetable oils, animal fats, cooking oil, and leftover restaurant grease through transesterification. The steps involved in the transesterification process are shown in Figure 1. Currently, biodiesel resources include Palm oil, Jatropha, Cottonseed oil, Rapeseed, Soybean, Linseed oil, Sesame oil, Sunflower oil, Karanja, Mahua oil, Linseed oil, neem oil, Algae, Waste cooking oil, and animal fats, among others [30-31]. Ethanol, another renewable option, contains 34% more oxygen by weight and serves as a cost-effective oxygenate. It can be naturally produced through fermentation using biomass sources like sugarcane, corn, sugar beet, molasses, and cassava root. Diesel engines running on ethanol have the potential to increase rural economies greatly. The process of making ethanol on a big scale includes steps like the fermentation of carbohydrates by yeast, followed by distillation, dehydration, and denaturing. Ethanol production starts with processing feedstocks, which include sugar-rich plants like sugarcane, starch-rich grains like corn, and cellulosic biomass. Grain feedstocks are milled into fine powders, whilst sugarcane and sugar beets are crushed and pressed to obtain juice. Enzymes are employed to transform starch-based feedstocks into fermentable sugars via liquefaction and saccharification. The resulting mixture is next fermented, in which yeast transforms the sugars to ethanol and carbon dioxide under regulated circumstances, usually for 48 to 72 hours. Ethanol vaporises first with a lower boiling point and is collected and condensed back into a liquid, yielding around 95% purity. The residual water is removed using molecular sieves, azeotropic distillation, or membrane technology to obtain anhydrous ethanol. Byproducts such as carbon dioxide can be recovered for industrial use, while solid wastes from grain fermentation, known as distillers grains, are used as nutrient-dense animal feed. This process enables the efficient generation of ethanol, a vital biofuel and chemical feedstock [32]. Figure 2 depicts the process involved in the ethanol manufacturing process.

Fuel characteristics are very important in determining how well fuel is mixed and burned. When examining the impact of biodiesel additives on a diesel engine's combustion, performance, and emission characteristics, researchers frequently focus on factors including density, calorific value, cetane number, viscosity, and flash point. These characteristics substantially impact how biodiesel blends interact inside the engine, affecting the effectiveness of combustion and overall engine performance.

Ethanol fuels have properties that improve a diesel engine's thermal efficiency, combustion behaviour, and exhaust pollutants. Alcohol's low viscosity enhances fuel atomisation and lowers injection resistance. Ethanol also contains oxygen molecules that help complete combustion and reduce exhaust pollutants. In addition, ethanol cools the engine more effectively during the intake and compression strokes than diesel because of its higher latent heat of vaporisation, which also improves the volumetric efficiency of the engine [33].

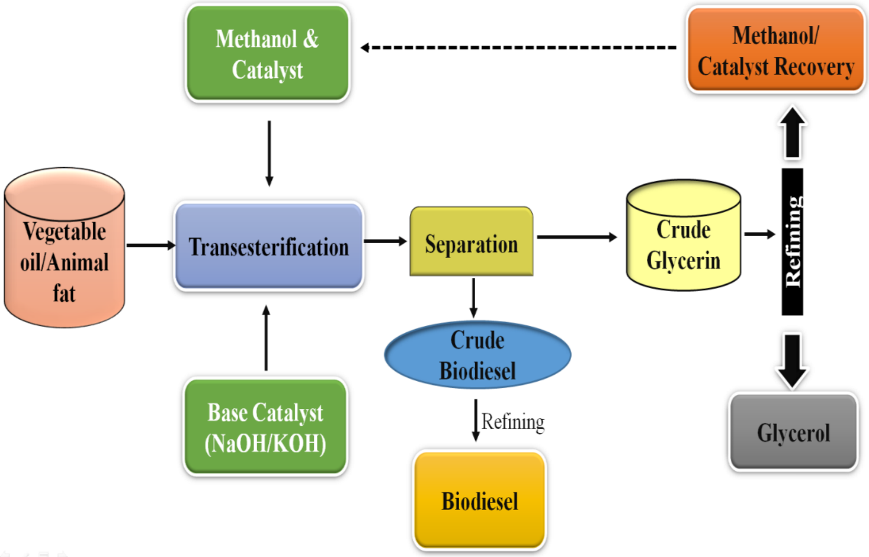

Figure 1. The production process of biodiesel

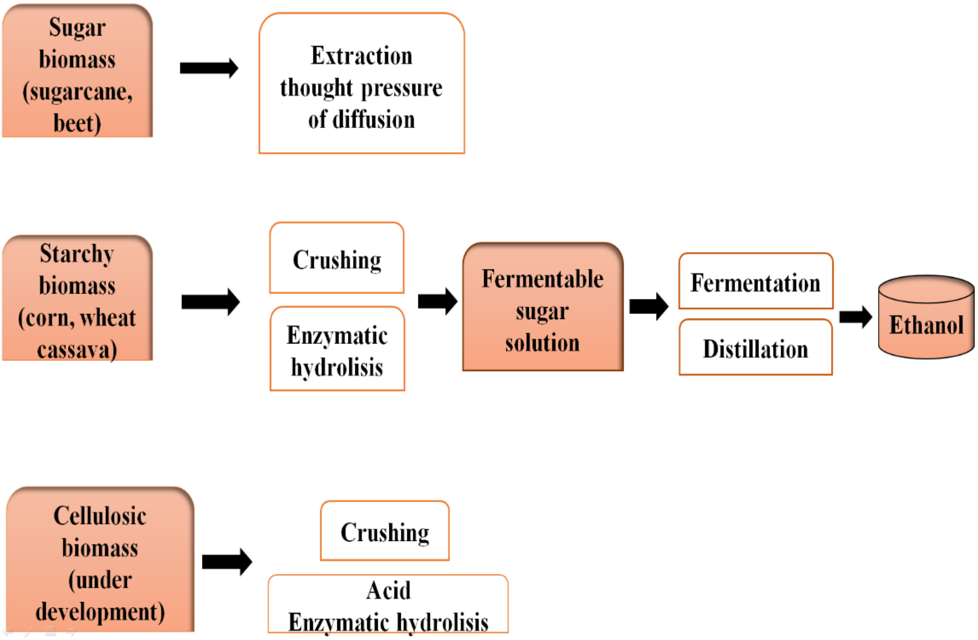

Figure 2. The steps involved in the ethanol production

Both ethanol and biodiesel have a variety of distinct chemical and physical characteristics. The quality of the feedstock, its fatty acid content, the kind of manufacturing and refining technique used, and post-production parameters are only a few of the variables that affect biofuel quality. When biodiesel-diesel-ethanol is combined, characteristics can be changed. The physicochemical properties of diesel, ethanol, and various biodiesel are shown in Table 1.

Table 1. **The physicochemical properties of various biodiesel, diesel, and ethanol blend** [34-36].

Properties(→) **Product (↓)**	**Density at 40 °C (kg/m^3)**	**Viscosity at 40 °C (mm^2/s)**	**Calorific Value (MJ/kg)**	**Cetane number**	**Flashpoint (°C)**
Diesel	830 - 850	2.5 - 3.11	42 - 44	50 - 53	50- 90
Ethanol (C_2H_5OH)	788 - 792	1.4	26.9 - 28.86	8 - 12	16
Jatropha biodiesel	865 - 880	3.7 - 5.8	38 - 42	46 – 55	163 - 238
Soybean biodiesel	885 - 890	4 - 4.3	37 - 38	>51	>120
Palm biodiesel	860 - 900	4.42	34 - 36	62 – 63	174
Karanja biodiesel	890	4.37 - 9.60	39 - 40	53	181
Waste cooking oil biodiesel	855 - 870	4.5 - 5.3	38 - 41	52	126
Algae biodiesel	860 - 883	4.47 - 5.66	33.2 - 41.36	48 - 55.4	115 - 178

3. Impact of diesel-biodiesel-ethanol blends on diesel engines

Researchers have looked at the efficiency and emissions characteristics of diesel engines running on DBE mixtures in many different countries. According to reports, many variables, including the kind of engine, its operating environment, the qualities of the fuel, and the concentration of the fuel, affect how well a DBE fuelled engine performs. The combination of ethanol with a mixture of diesel and biodiesel in diesel engines appears as a potential course of action as the search for cleaner and more sustainable energy options grows increasingly intense. The complex interactions between ethanol, diesel, and biodiesel are examined in this section in the context of the combustion characteristics, engine performance, emissions profiles, and associated difficulties of diesel engines as illustrated in Table 2.

Table 2. **The impact of DBE blend on performance, combustion, and emission**

Authors and Year	Types of engines	Blend Composition	Additives	Perfor-mance	Com-bustion	Emission
Aydın and Ogüt, 2017 [37]	Single-cylinder, 4-stroke, water-cooled. 15HP @ 2600rpm	D100, B2.5M2.5D95, B5M5D90, B5M2.5D92.5, B2.5M5D92.5, Safflower BD M: Bioethanol	--	Torque ↑ BP ↓ BSFC ↑		CO ↑ HC ↑ CO_2 ↑ SO_2 ↓ NOx ↑
Geo et al., 2017 [38]	Kirloskar TAF-1 single cylinder, air-cooled, direct injection, 4-stroke diesel engine	Diesel RSO (Rape seed oil) (75% and 100%) Ethanol (0-45%)	--	BTE ↑	$P_{cyl\ press.}$ ↑ Max rate of pressure rise ↑ ID ↑ CD ↓	NOx ↑ Smoke ↓ CO ↑ HC ↑
Guedes et al., 2018 [39]	4-stroke, 4-cylinder CI engine model 4.10 TCA	Diesel Biodiesel (7, 15%) Ethanol (0-15%)	1% bio co-solvent	BSFC ↓	P_{max} ↑ ID ↑	--
Shamun et al., 2019 [40]	Single-cylinder, 4-stroke, watercooled, common rail 1.9-liter Fiat/GM JTDengine	Diesel Soybean biodiesel (14%, 17%) Ethanol (15%, 30%)			ID ↑	CO ↑ THC ↑ NOx ↓ PM ↓
Madiwale et al., 2019 [41]	4-stroke, single cylinder, VCR diesel engine @1500rpm CR:18	Diesel Cotton oil BD Jatropha BD Palm oil BD Soybean oil BD (20, 40, 60, 80%) Ethanol (5%)		BP ↑ BTE ↑ BSFC ↓	--	--
Tongroon et al., 2019 [42]	4-stroke, 4-cylinder, CRDI diesel engine 85 kW@3600 rpm	B3E5, B7E5 B10E10 Palm oil BD		Torque ↓ BP ↓ BSFC ↑	HRR ↑	NOx ↑ HC ↑
Pradelle et al., 2019 [43]	4-stroke, 4-cylinder, DI diesel engine CR: 15.8:1 107 kW @ 2600 rpm	Diesel BD (15%) Ethanol (0-20%)	10ppm Sulphur	Torque ↓ ithe ↑ BSFC↑ η(mech) ↓	P_{max} ↓ ID ↑ HRR ↑	--

Authors and Year	Types of engines	Blend Composition	Additives	Perfor-mance	Com-bustion	Emission
Khoobbakht et al., 2019 [44]	4-cylinder DI diesel engine, model OM 314 CR- 17:1 81 kW @ 2800 rpm	Diesel Rapeseed BD Ethanol RSM		BP ↓ BTE ↓ BSFC ↑		
Sharma et al., 2019 [45]	Single-cylinder, Kirloskar, Model TV1, 4-stroke, DI diesel engine, CR- 17.5:1 5.2 kW (7 BHP) @1500 rpm	Diesel Soybean BD Biogas		BTE ↓		CO ↓ HC ↓ NOx ↑
Venu et al., 2020 [46]	Kirloskar make, 4-stoke, 1-cylinder, DI engine 4.4kW @ 1500rpm.	70% diesel, 20% Jatropha BD, 10% ethanol	Alumina (Al_2O_3) 10ppm, 20ppm and 30ppm	BSEC ↑ BTE ↑		NOx ↑ Smoke ↓ CO ↓ HC ↓
Heidari Maleniet et al., 2020 [47]	Single-cylinder, 4-stoke air-cooled diesel engine (DICOM model, Italy)	Diesel Fish waste oil BD (10%) Ethanol (2, 4, 6%)	Graphene Quantum Dot (GQD) (60ppm)	Torque ↑ BP ↑ BSFC ↓		CO ↓ HC ↓ CO_2 ↑ NOx ↓
Gawale et al., 2020 [48]	1-cylinder, VCR HCCI diesel engine, 3.5 kW @ 1500rpm	Diesel Neem BD (20%) Ethanol		BTE↑	ID ↑ SOC ↑ In-cylinder pressure ↓	NOx ↓ Smoke ↓ CO ↑ HC ↑
Qi et al., 2021 [49]	4-cylinder, 4-stroke, Common rail direct injection, Turbocharged inter-cooled 113 kW@2300 rpm EGR	D60P30E10 D50P40E10 D40P30E30 Palm BD		BSFC ↑ BTE ↑	P_{max} ↑ ID ↑ HRR ↑	HC ↓ NOx ↑ PM ↓
Shrivastava et al., 2021 [50]	4-S, 1 cylinder, Multi-fuel, VCR, CR-17.5, 3.5 KW @ 1500 rpm, Taguchi optimization	Diesel Karanja BD (20, 25, 30%) Ethanol (5, 10%)		BTE ↓ BSFC ↑ EGT ↑	Pmax, IMEP, SOC, EOC, CD, ID, HRR all similar to diesel	CO ↓ CO_2 ↑ HC ↓ NOx ↓
Shirneshan et al., 2021 [51]	4-cylinder, 4-stroke, DI and water-cooled diesel engine CR- 16:1 82 kW at 2800 RPM RSM Genetic Algorithm	Waste cooking oil BD Ethanol		Torque ↓ BP ↓ BSFC ↑		Smoke ↓ NOx ↓ CO ↓

Authors and Year	**Types of engines**	**Blend Composition**	**Additives**	**Perfor-mance**	**Com-bustion**	**Emission**
Srikanth et al., 2021 [52]	Kirloskar, TV 1, Single cylinder, 4-S, Water-cooled CR-17.5:1 5.5kW @ 3000rpm	DE5B10, DE10B10, DE15B10, DE5B20, DE10B20, DE15B20 Niger seed oil BD		BTE ↑ BSFC ↑		CO_2 ↑ Smoke ↓ NOx ↑
Janakiraman et al., 2022 [53]	Kirloskar TAF-1, 4-stroke, single-cylinder diesel Engine CR-17.6:1 5.2 kW and 1500 rpm	Diesel 70% *Garcinia* oil BD 20% Ethanol 10%	Titanium dioxide (TiO_2) (35, 45, 55, 65 ppm)	BTE ↑ BSEC ↓	MFB ↓ In-cylinder pressure ↑ ID ↓	Smoke ↓ CO ↓ HC ↓ NOx ↑
Kesharvani et al., 2022 [54]	Single cylinder, 4-S, 3.7 kW @ 1500rpm Kirloskar Model TV 1 diesel engine	D100 B10 B20 B5E5 B10E10 Algae BD		BTE ↓ BSFC ↑	Cyl. Pressure ↑ HRR ↑	CO_2 ↓ Smoke ↓ PM ↓ NOx ↓
M M N Awalludinet al., 2022 [55]	4-S, 1-cylinder, YANMAR TF120 CR-17.7:1, water cooled 9 kW at 2400rpm	E5B5D90 E10B10D80 E15B15D7 Palm oil BD			In-cylinder pressure ↑ HRR ↑ ID ↑	
Sathish et al., 2022 [56]	4-S, 1-cylinder, diesel engine	D100 B100 D80B20 B80E20 D60B20E20 Azadirachta indica BD		BTE ↑	HRR ↑	CO ↓ HC ↓ Smoke ↓ NOx ↑
Zuo et al., 2022 [57]	Turbocharged, 4-cylinder CRDI engine operated at various loads of 1800 rpm.	D100 D90PHCME10 D80PHCME20 D70PHCME30 D80PHCME20 D90PHCME5E5 D80PHCME10E10 D70PHBCME15E15 PHCME: Partial hydrogenated castor methyl ester		BSFC ↑	HRR ↓ CP ↓	CO ↑ HC ↑ CO_2 ↑

Authors and Year	Types of engines	Blend Composition	Additives	Perfor-mance	Com-bustion	Emission
Bhargavi et al.,2022 [58]	4-S, 1-cylinder, water-cooled DI diesel engine 4.4kW @ 1500rpm	D100 D70W20E10 D70W20E15 D70W20E20 Waste plastic oil		BTE ↑ BSFC ↓		CO ↓ HC ↓
Swamy et al., 2022 [59]	Kirloskar make, Single-cylinder, 4-stroke, Direct injection diesel engine, 5.2kW @1500rpm	Water with diesel emulsion Water with diesel emulsion + Ethanol		BTE ↑		Smoke ↓ CO ↓ HC ↓ NOx ↓
Chuepeng et al.,2023 [60]	single-cylinder air-cooled DI diesel engine (Mitsuki, MIT-186FG model). CR-17.5:1 8.5 kW at 3000 rpm.	Diesel Palm BD Ethanol		BTE ↓ BSFC ↑		CO_2 ↓ CO ↑ NO ↓ PM ↓
Rao and Reddy, 2023 [61]	CRDI four-cylinder four-stroke diesel engine,	Diesel Acid oil BD (50%) Ethanol (4, 8, 12%)		BTE ↓ BSFC ↑		CO ↑ HC ↑ NOx ↓
Kurre et al., 2023 [62]	4-S, 1-cylinder, water-cooled, 3.5kW @1500rpm	D100 BD30D69E1 BD30D68E2 BD30D67E3 BD30D66E4 BD30D65E5 Jatropha BD	Titanium dioxide (TiO_2) (100ppm)	BTE ↓ BSFC ↑		CO ↓ CO2 ↓ HC ↓ Smoke ↓ NOx ↑
Kharkwal et al., 2023 [63]	Single-cylinder, 4-stroke, naturally aspirated, water-cooled, DI diesel engine	B20E5 B20E10 B20E20 B20DEE3 B20DEE5 B20DEE10 Waste cooking oil BD	Diethyl ether	BTE ↓ BSFC ↑	HRR ↓	CO_2 ↓ PM ↑ Smoke ↑ NOx ↑
Nagwan et al., 2023 [64]	Kirloskar, 4.4 kW, constant speed, 1-Cylinder, 4-stroke, water-cooled engine CR-17.5:1	D100 B10 B10E10, B10E20 B20 B20E10 B20E20 Hemp oil BD		BP ↑ BTE ↑ BSFC ↓		

From the literature survey, it was observed that the use of blends containing ethanol, diesel, and biodiesel presents a dynamic combination of attributes that can greatly affect combustion characteristics. The ignition process is accelerated by a higher octane rating of ethanol, while biodiesel's greater cetane number plus higher oxygen concentration improve combustion efficiency by enhancing the oxygen-to-fuel ratio. This elevated cetane number improves ignition quality, leading to more efficient combustion. The presence of oxygen in biodiesel enhances a more environmentally friendly combustion process by aiding in the thorough oxidation of fuel, leading to cleaner emissions., reducing emissions of particulate matter and certain pollutants. Ethanol, with its high-octane number, further contributes to improved ignition in the blend. Its oxygen content enhances combustion efficiency, and when combined with biodiesel, the overall oxygenation of the blend can lead to better fuel oxidation. Furthermore, the combined impacts of ethanol, diesel, and biodiesel significantly influence engine performance. It was found that when the ethanol proportion expanded, engine performance declined and unburned HC and NOx emissions also increased. The findings of the heat release study made it clear that the pilot combustion was delayed with an increase in the ethanol fraction to allow for the formation of unburned HC during the extended ignition delay. Moreover, encouraging nitrogen oxide emissions in the exhaust stream was the greater HRR. Moreover, biodiesel's lubricity properties benefit engine components by reducing wear and tear. Overall, blending diesel with biodiesel and ethanol enhances combustion efficiency and addresses environmental concerns by lowering emissions and promoting the use of renewable resources. However, it's crucial to consider factors such as blend ratios, engine compatibility, and local regulations when adopting these alternative fuel blends in diesel engines.

These fuels can be combined to provide increased BTE, more torque, and more evenly distributed power. The oxygen-rich nature of ethanol and the lubricity-improving characteristics of biodiesel can enhance the engine's durability. Moreover, this blend has the capacity to decrease the release of various pollutants. In addition to lowering NOx emissions, the simultaneous use of biodiesel also helps to address other environmental issues.

4. Conclusions

The findings presented in this comprehensive review paper shed light on the complex interplay between biodiesel content and ethanol with various fuel additives, and their impact on combustion properties, engine efficiency, and emissions. It is clear from the research that increasing ethanol content can enhance combustion properties, but it may come at the cost of reduced power output and increased emissions of certain pollutants, such as HC and NOx. However, the optimisation of fuel blends and additive formulations remains a complex challenge, influenced by factors such as engine type, load variation, injection conditions, and in-cylinder pressure. This study underscores several key conclusions:

Firstly, the physicochemical properties of these blends are intricately linked to the feedstocks utilised, with variations in intensity and types of feedstocks leading to notable differences in the characteristics of the blends. Secondly, the reduced brake power observed in diesel-biodiesel-ethanol (DBE) blends is attributed to their lower heating values compared to traditional diesel. This reduction results in higher specific fuel consumption, underlining the importance of considering the energy content of alternative fuel blends.

Furthermore, the effectiveness of ethanol-biodiesel-diesel blends in reducing carbon monoxide (CO) emissions is highlighted due to their higher oxygen content, promoting more complete combustion. On the other hand, the elevated nitrogen oxide (NOx) emissions associated with blends with higher oxygen content, such as biodiesel-alcohol blends, are acknowledged. However, the conclusion suggests that techniques like Exhaust Gas Recirculation (EGR) can serve as effective countermeasures to mitigate these NOx emissions, providing potential solutions for emission control strategies.

The discussion on tertiary blends points out a positive outcome, indicating a reduction in hydrocarbon (HC) emissions in diesel engines. This decrease is credited to the increased oxygen content found in both biodiesel and ethanol, promoting a more thorough combustion process. Moreover, the reduction in particulate matter (PM) emissions in blends of ethanol, biodiesel, and diesel is explained by the lower aromatic compound content in biofuels and their higher oxygen content, contributing to cleaner combustion processes.

Finally, the varying results in carbon dioxide (CO_2) emissions across studies are addressed. The majority of research indicates a rise in CO2 emissions, linked to the elevated oxygen content in biofuels that improves the quality of combustion. This nuanced understanding of the complex interactions and outcomes of biodiesel-ethanol-diesel blends in diesel engines highlights the need for a tailored approach in formulating and implementing alternative fuel strategies to achieve optimal environmental and performance outcomes.

As a whole, the literature review suggests that diesel engine performance can be enhanced and harmful exhaust emissions can be decreased by using mixtures of diesel, biodiesel, and ethanol. These improvements come from the blends' higher physicochemical qualities over conventional diesel fuel. This study demonstrates how biodiesel-alcohol blends can be used as greener substitutes, opening the door to cleaner and more effective diesel engine technology. Further exploration and application of these blends hold promise for reducing the environmental impact of the transportation sector.

5. Challenges and future recommendations

The integration of ethanol with diesel and biodiesel fuels in Compression Ignition (CI) engines presents both opportunities and challenges. This summary highlights the key challenges faced in this integration and offers future recommendations to enhance the effective utilization of ethanol in CI engines.

5.1. Challenges

Blending Compatibility: It is challenging to produce a stable and uniform mixture of ethanol with diesel or biodiesel due to its dissimilar properties, such as density and viscosity. Important issues include proper mixing and avoiding phase separation.

Cetane number: A lower cetane number for ethanol than for diesel results in longer ignition delays and a higher risk of engine knocking. The solution to this problem is essential for preserving engine performance.

Corrosion and material compatibility: Because ethanol is corrosive, it has the potential to harm several engine parts and materials used in fuel systems. To avoid wear and tear, it is crucial to guarantee compatibility with engine materials.

Cold Flow Properties: Ethanol has poor cold flow properties, leading to issues like waxing and gelling in cold weather conditions. Finding additives or methods to improve low-temperature operability is necessary.

These properties also have critical issues with biodiesel. Cold flow qualities refer to how well biodiesel performs at low temperatures, which influences its ability to flow and pump under cold situations. Common difficulties include a high pour point, where biodiesel solidifies at greater temperatures than conventional diesel, and a high cloud point, where crystals form, causing the fuel to cloud. Furthermore, the cold filter plugging point (CFPP) can be problematic since biodiesel can clog filters at low temperatures, and increased viscosity can hamper fuel injection and combustion. To address these issues, strategies such as blending biodiesel with conventional diesel, adding cold flow improvers, selecting feedstocks with superior cold flow properties, winterising biodiesel, and installing fuel heating systems can be used to improve performance and reliability in colder climates.

Lubricity: Ethanol possesses lower lubricity than diesel, which may cause increased wear on fuel injection systems. Lubricity enhancers or engine modifications may be required.

Emission Control: Ethanol blends, including nitrogen oxides (NOx) and particulate matter (PM), can impact emissions. Balancing emissions reduction with maintaining engine efficiency is a significant challenge.

5.2. Future Recommendations

Research and Development: It is crucial to keep looking into the characteristics of ethanol-diesel and ethanol-biodiesel mixes. Fuel compositions may be improved by better understanding how they behave under different circumstances.

Engine Modifications: CI engines may need modifications, such as changes in injection timing and combustion chamber design, to accommodate ethanol blends effectively. Engine retrofitting can enhance performance.

Fuel Additives: Developing effective additives can address challenges related to corrosion, lubricity, and cold flow properties. Additives can stabilize blends and improve their overall performance.

Advanced Injection Systems: Advanced fuel injection systems, including electronic control systems, can optimize the combustion process, mitigating issues like ignition delay and emissions.

Standardization and Regulation: Establishing industry standards and regulations for ethanol-diesel and ethanol-biodiesel blends ensures quality and safety. Clear guidelines promote widespread adoption.

Sustainable Feedstocks: Exploring sustainable and diverse feedstocks for ethanol production, such as cellulosic materials, contributes to environmental sustainability and reduces competition with food resources.

Public Awareness: Raising awareness about the benefits of ethanol blends, including reduced emissions and enhanced energy security, can drive consumer acceptance and demand.

In conclusion, addressing the challenges associated with ethanol utilization in CI engines requires a multidisciplinary approach involving research, technology development, and regulatory initiatives. By focusing on these recommendations, the effective integration of ethanol with diesel and biodiesel fuels can be achieved, leading to cleaner, more efficient, and sustainable transportation solutions.

REFERENCES

[1] *Rao, G. P., & Prasad, L. S. V.* Combined influence of compression ratio and exhaust gas recirculation on the diverse characteristics of the diesel engine fueled with novel palmyra biodiesel blend. *Energy Conversion and Management: X*, 14, 100185, 2022. https://doi.org/10.1016/j.ecmx.2022.100185

[2] *Kumar, S., & Gautam, R*. Energy and exergy assessment of diesel-tallow biodiesel blend in compression ignition engine for engine design variables. *Sustainable Energy Technologies and Assessments*, 57, 103305, 2023. https://doi.org/10.1016/j.seta.2023.103305

[3] *Liang, J., Zhang, Q., Chen, Z., & Zheng, Z.* The effects of EGR rates and ternary blends of biodiesel/n-pentanol/diesel on the combustion and emission characteristics of a CRDI diesel engine. Fuel, 286, 119297, 2021. https://doi.org/10.1016/j.fuel.2020.119297

[4] *Yadav, P. S., Said, Z., Gautam, R., Raman, R., & Caliskan, H.* Novel investigation on atomization, performance, and emission characteristics of preheated jatropha oil methyl ester and ethyl ester. *Energy*, 270, 126870, 2023. https://doi.org/10.1016/j.energy.2023.126870

[5] *Yoon, S. K., Ge, J. C., & Choi, N. J*. Influence of fuel injection pressure on the emissions characteristics and engine performance in a CRDI diesel engine fueled with palm biodiesel blends. *Energies*, 12(20), 3837, 2019.https://doi.org/10.3390/en12203837

[6] *Singh, T. S., & Verma, T. N.* Biodiesel production from Momordica Charantia (L.): Extraction and engine characteristics. *Energy*, 189, 116198, 2019. https://doi.org/10.1016/j.energy.2019.116198

[7] *Wang, S., Karthickeyan, V., Sivakumar, E., & Lakshmikandan, M.* Experimental investigation on pumpkin seed oil methyl ester blend in diesel engine with various injection pressure, injection timing and compression ratio. *Fuel*, 264, 116868, 2020. https://doi.org/10.1016/j.fuel.2019.116868

[8] *Kavitha, K. R., Beemkumar, N., & Rajasekar, R*. Experimental investigation of diesel engine performance fuelled with the blends of Jatropha curcas, ethanol, and diesel. *Environmental Science and Pollution Research*, 26, 8633-8639, 2019. https://doi.org/10.1007/s11356-019-04288-x

[9] *Kumar, M., Gautam, R., & Ansari, N. A.* Performance characteristics optimization of CRDI engine fuelled with a blend of sesame oil methyl ester and diesel fuel using response surface methodology approach. *Frontiers in Mechanical Engineering*, 9, 1049571, 2023. https://doi.org/10.3389/fmech.2023.1049571

[10] *Sudalaiyandi, K., Alagar, K., VJ, M. P., & Madhu, P.* Performance and emission characteristics of diesel engine fueled with ternary blends of linseed and rubber seed oil biodiesel. *Fuel*, 285, 119255, 2021. https://doi.org/10.1016/j.fuel.2020.119255

[11] *Santaraite, M., Sendzikiene, E., Makareviciene, V., &Kazancev, K.* Biodiesel production by lipase-catalyzed in situ transesterification of rapeseed oil containing a high free fatty acid content with ethanol in diesel fuel media. *Energies*, 13(10), 2588, 2020. https://doi.org/10.3390/en13102588

[12] *Jin, C., Zhang, X., Wang, X., Xiang, Y., Cui, X., Yin, Z., ... & Liu, H.* Effects of polyoxymethylene dimethyl ethers on the solubility of ethanol/diesel and hydrous

ethanol/diesel fuel blends. *Energy Science & Engineering*, 7(6), 2855-2865, 2019. https://doi.org/10.1002/ese3.466

[13] *Kim, H. Y., Ge, J. C., & Choi, N. J*. Effects of ethanol–diesel on the combustion and emissions from a diesel engine at a low idle speed. *Applied Sciences*, 10(12), 4153, 2020. https://doi.org/10.3390/app10124153

[14] *Wu, Y., Zhang, X., Zhang, Z., Wang, X., Geng, Z., Jin, C., ... & Yao, M*. Effects of diesel-ethanol-THF blend fuel on the performance and exhaust emissions on a heavy-duty diesel engine. *Fuel*, 271, 117633, 2020. https://doi.org/10.1016/j.fuel.2020.117633

[15] *Sahu, T. K., Kshatri, R., & Shukla, P. C.* Impact of ethanol on combustion, performance, and emission characteristics of diesel engine. In Alcohol as an Alternative Fuel for Internal Combustion Engines (pp. 251-266), 2021. *Singapore: Springer Singapore*.

[16] *Al-Esawi, N., Al Qubeissi, M., &Kolodnytska, R.* The impact of biodiesel fuel on ethanol/diesel blends. Energies, 12(9), 1804, 2019. https://doi.org/10.3390/en12091804

[17] *İlçin, K., & Altun, Ş*. Effect of biodiesel addition in a blend of isopropanol-butanol-ethanol and diesel on combustion and emissions of a CRDI engine. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 44(2), 4727-4739, 2022. https://doi.org/10.1080/15567036.2021.1928797

[18] *Klajn, F. F., Gurgacz, F., Lenz, A. M., Iacono, G. E. P., Souza, S. N. M. D., & Ferruzzi, Y*. Comparison of the emissions and performance of ethanol-added diesel–biodiesel blends in a compression ignition engine with those of pure diesel. *Environmental technology*, 41(4), 511-520, 2020. https://doi.org/10.1080/09593330.2018.1504122

[19] *El-Seesy, A. I., Hassan, H., Ibraheem, L., He, Z., & Soudagar, M. E. M*. Combustion, emission, and phase stability features of a diesel engine fueled by Jatropha/ethanol blends and n-butanol as co-solvent. *International Journal of Green Energy*, 17(12), 793-804, 2022. https://doi.org/10.1080/15435075.2020.1798770

[20] *Gautam, R., & Kumar, N.* Performance emission and combustion studies of diesel engine on Jatropha ethyl ester and its higher alcohol blends. *International Journal of Global Warming*, 14(2), 159-169, 2018. https://doi.org/10.1504/IJGW.2018.090177

[21] *Padmanabhan, S., Giridharan, K., Stalin, B., Kumaran, S., Kavimani, V., Nagaprasad, N., ... &Krishnaraj, R.* Energy recovery of waste plastics into diesel fuel with ethanol and ethoxy ethyl acetate additives on circular economy strategy. *Scientific Reports*, 12(1), 5330, 2022. https://doi.org/10.1038/s41598-022-09148-2

[22] *Nour, M., Attia, A. M., & Nada, S. A*. Improvement of CI engine combustion and performance running on ternary blends of higher alcohol (Pentanol and Octanol)/ hydrous ethanol/diesel. *Fuel*, 251, 10-22, 2019. https://doi.org/10.1016/ j.fuel.2019.04.026

[23] *Krishna, S. M., Salam, P. A., Tongroon, M., & Chollacoop, N.* Performance and emission assessment of optimally blended biodiesel-diesel-ethanol in diesel engine generator. *Applied Thermal Engineering*, 155, 525-533, 2019. https://doi.org/ 10.1016/j.applthermaleng.2019.04.012

[24] *Aengchuan, P., Wiangkham, A., Klinkaew, N., Theinnoi, K., &Sukjit, E.* Prediction of the influence of castor oil–ethanol–diesel blends on single-cylinder diesel engine characteristics using generalized regression neural networks (GRNNs). *Energy Reports*, 8, 38-47, 2022. https://doi.org/10.1016/j.egyr.2022.10.113

[25] *Zaharin, M. S. M., Abdullah, N. R., Najafi, G., Sharudin, H., & Yusaf, T.* Effects of physicochemical properties of biodiesel fuel blends with alcohol on diesel engine performance and exhaust emissions: A review. *Renewable and Sustainable energy reviews*, 79, 475-493, 2017. http://dx.doi.org/10.1016/j.rser.2017.05.035

[26] *Mofijur, M. G. R. M., Rasul, A. M., Hyde, J., Azad, A. K., Mamat, R., & Bhuiya, M. M. K.* Role of biofuel and their binary (diesel–biodiesel) and ternary (ethanol–biodiesel–

diesel) blends on internal combustion engines emission reduction. *Renewable and Sustainable Energy Reviews*, 53, 265-278, 2016. http://dx.doi.org/10.1016/ j.rser.2015.08.046

[27] *Lee, C. C., Tran, M. V., Tan, B. T., Scribano, G., & Chong, C. T.* A comprehensive review on the effects of additives on fundamental combustion characteristics and pollutant formation of biodiesel and ethanol. *Fuel*, 288, 119749, 2021. https://doi.org/10.1016/j.fuel.2020.119749

[28] *Kumar, M., Ansari, N. A., Sharma, A., Singh, V. K., Gautam, R., & Singh, Y*. Prediction of an optimum engine response based on different input parameters on common rail direct injection diesel engine: A response surface methodology approach. *Scientia Iranica*, 28(6), 3181-3200, 2021.https://doi.org/10.24200/sci.2021.56745.4885

[29] *Chandel, A. K., Albarelli, J. Q., Santos, D. T., Chundawat, S. P., Puri, M., & Meireles, M. A. A.* Comparative analysis of key technologies for cellulosic ethanol production from Brazilian sugarcane bagasse at a commercial scale. *Biofuels, bioproducts and biorefining*, 13(4), 994-1014, 2019.https://doi.org/10.1186/s40643-022-00573-9

[30] *Kumar, M., Ansari, N. A., & Samsher.* Investigation of combustion, performance and emission of aluminium oxide nanoparticles as additives in CI engine fuels: a review. *Advances in Manufacturing and Industrial Engineering: Select Proceedings of ICAPIE* 2019, 1055-1063, 2021.

[31] *Sakthivel, R., Ramesh, K., Purnachandran, R., & Shameer, P. M.* A review on the properties, performance and emission aspects of the third-generation biodiesels. *Renewable and Sustainable Energy Reviews*, 82, 2970-2992, 2018. https://doi.org/ 10.1016/j.rser.2017.10.037

[32] *Kumar, M., Singh, V. K., Sharma, A., Ansari, N. A., Gautam, R., & Singh, Y.* Effect of fuel injection pressure and EGR techniques on various engine performance and emission characteristics on a CRDI diesel engine when run with linseed oil methyl ester. *Energy & Environment*, 33(1), 41-63, 2022. https://doi.org/10.1177/0958305X20983477

[33] *Siwale, L., & Bereczky, A.* Effect of n-butanol fuel additive to methanol-gasoline blend on combustion and emission characteristics in a single cylinder spark ignition engine. *International Journal of Petrochemical Science & Engineering*, 3(3), 2018. https://doi.org/10.15406/ipcse.2018.03.00081

[34] *Goga, G., B. S. Chauhan, S. K. Mahla, H. M. Cho, A. Dhir and H. C. J. M. T. P. Lim* "Properties and characteristics of various materials used as biofuels: A review." **5**(14): 28438-28445, 2018. https://doi.org/10.1016/j.matpr.2018.10.130.

[35] *Suresh, M., Jawahar, C. P., & Richard, A*. A review on biodiesel production, combustion, performance, and emission characteristics of non-edible oils in variable compression ratio diesel engine using biodiesel and its blends. Renewable and Sustainable Energy Reviews, 92, 38-49, 2018. https://doi.org/10.1016/ j.rser.2018.04.048

[36] *Ghadikolaei, M. A., Yung, K. F., Cheung, C. S., & Lau, P. C.* hemical properties and composition of PM emitted from a diesel engine fueled with ternary fuel (diesel-biodiesel-ethanol) in blended and fumigation modes. *Fuel*, 251, 368-382, 2019. https://doi.org/10.1016/j.fuel.2019.04.007

[37] *Aydın, F., & Öğüt, H.* Effects of using ethanol-biodiesel-diesel fuel in single cylinder diesel engine to engine performance and emissions. *Renewable energy*, 103, 688-694, 2017. http://dx.doi.org/10.1016/j.renene.2016.10.083

[38] *Geo, V. E., Sonthalia, A., Nagarajan, G., & Nagalingam, B.* Studies on performance, combustion and emission of a single cylinder diesel engine fuelled with rubber seed oil and its biodiesel along with ethanol as injected fuel. *Fuel*, 209, 733-741, 2017. http://dx.doi.org/10.1016/j.fuel.2017.08.036

[39] *Guedes, A. D. M., Braga, S. L., &Pradelle, F.* Performance and combustion characteristics of a compression ignition engine running on diesel-biodiesel-ethanol (DBE) blends–Part 2: Optimization of injection timing. *Fuel*, 225, 174-183, 2018. https://doi.org/10.1016/j.fuel.2018.02.120

[40] *Shamun, S., Belgiorno, G., Di Blasio, G., Beatrice, C., Tunér, M., &Tunestål, P*. Performance and emissions of diesel-biodiesel-ethanol blends in a light duty compression ignition engine. *Applied Thermal Engineering*, 145, 444-452, 2018. https://doi.org/10.1016/j.applthermaleng.2018.09.067

[41] *Madiwale, S., Karthikeyan, A., & Bhojwani, V.* Properties investigation and performance analysis of a diesel engine fuelled with Jatropha, Soybean, Palm and Cottonseed biodiesel using Ethanol as an additive. *Materials Today: Proceedings*, 5(1), 657-664, 2018. https://doi.org/10.1016/j.matpr.2017.11.130

[42] *Tongroon, M., Saisirirat, P., Suebwong, A., Aunchaisri, J., Kananont, M., &Chollacoop, N.* Combustion and emission characteristics investigation of diesel-ethanol-biodiesel blended fuels in a compression-ignition engine and benefit analysis. *Fuel*, 255, 115728, 2019. https://doi.org/10.1016/j.fuel.2019.115728

[43] *Pradelle, F., Braga, S. L., de Aguiar Martins, A. R. F., Turkovics, F., &Pradelle, R. N. C.* Performance and combustion characteristics of a compression ignition engine running on diesel-biodiesel-ethanol (DBE) blends–Potential as diesel fuel substitute on an Euro III engine. *Renewable energy*, 136, 586-598, 2019. https://doi.org/10.1016/j.renene.2019.01.025

[44] *Khoobbakht, G., Karimi, M., &Kheiralipour, K.* Effects of biodiesel-ethanol-diesel blends on the performance indicators of a diesel engine: A study by response surface modeling. *Applied Thermal Engineering*, 148, 1385-1394, 2019. https://doi.org/10.1016/j.applthermaleng.2018.08.025

[45] *Sharma, A., Ansari, N. A., Pal, A., Singh, Y., &Lalhriatpuia, S.* Effect of biogas on the performance and emissions of diesel engine fuelled with biodiesel-ethanol blends through response surface methodology approach. Renewable *Energy*, 141, 657-668, 2019. https://doi.org/10.1016/j.renene.2019.04.031

[46] *Venu, H., Raju, V. D., Lingesan, S., & Soudagar, M. E. M*. Influence of Al2O3nano additives in ternary fuel (diesel-biodiesel-ethanol) blends operated in a single cylinder diesel engine: Performance, Combustion and Emission Characteristics. *Energy*, 215, 119091, 2021. https://doi.org/10.1016/j.energy.2020.119091

[47] *Heidari-Maleni, A., Gundoshmian, T. M., Karimi, B., Jahanbakhshi, A., &Ghobadian, B.* A novel fuel based on biocompatible nanoparticles and ethanol-biodiesel blends to improve diesel engines performance and reduce exhaust emissions. *Fuel*, 276, 118079, 2020. https://doi.org/10.1016/j.fuel.2020.118079

[48] *Gawale, G. R., & Srinivasulu, G. N.* Experimental investigation of ethanol/diesel and ethanol/biodiesel on dual fuel mode HCCI engine for different engine load conditions. *Fuel*, 263, 116725, 2020. https://doi.org/10.1016/j.fuel.2019.116725

[49] *Qi, D., Ma, L., Chen, R., Jin, X., & Xie, M.* Effects of EGR rate on the combustion and emission characteristics of diesel-palm oil-ethanol ternary blends used in a CRDI diesel engine with double injection strategy. *Applied Thermal Engineering*, 199, 117530, 2021. https://doi.org/10.1016/j.applthermaleng.2021.117530

[50] *Shrivastava, K., Thipse, S. S., & Patil, I. D.* Optimization of diesel engine performance and emission parameters of Karanja biodiesel-ethanol-diesel blends at optimized operating conditions. *Fuel*, 293, 120451, 2021. https://doi.org/10.1016/j.fuel.2021.120451

[51] *Shirneshan, A., Bagherzadeh, S. A., Najafi, G., Mamat, R., & Mazlan, M*. Optimization and investigation the effects of using biodiesel-ethanol blends on the performance and emission characteristics of a diesel engine by genetic algorithm. *Fuel*, 289, 119753, 2021. https://doi.org/10.1016/j.fuel.2020.119753

[52] *Srikanth, H. V., Sharanappa, G., Manne, B., & Kumar, S. B.* Niger seed oil biodiesel as an emulsifier in diesel-ethanol blends for compression ignition engine. *Renewable Energy*, 163, 1467-1478, 2021. https://doi.org/10.1016/j.renene.2020.07.010

[53] *Janakiraman, S., Lakshmanan, T., & Raghu, P*. Experimental investigative analysis of ternary (diesel+ biodiesel+ bio-ethanol) fuel blended with metal-doped titanium oxide nanoadditives tested on a diesel engine. *Energy*, 235, 121148, 2021. https://doi.org/10.1016/j.energy.2021.121148

[54] *Kesharvani, S., Dwivedi, G., Verma, T. N., & Verma, P.* The experimental investigation of a diesel engine using ternary blends of algae biodiesel, ethanol and diesel fuels. *Energies*, 16(1), 229, 2022. https://doi.org/10.3390/en16010229

[55] *NA, M. M., Hagos, F. Y., Abdulah, A. A., & Karim, Z. A. A.* Combustion characteristics of tri-fuel (diesel-ethanol-biodiesel) emulsion fuels in CI engine with micro-explosion phenomenon attributes. *Fuel*, 312, 122933, 2022. https://doi.org/10.1016/j.fuel.2021.122933

[56] *Sathish, T., Mohanavel, V., Arunkumar, M., Rajan, K., Soudagar, M. E. M., Mujtaba, M. A., ... & Sivakumar, S.* Utilization of Azadirachta indica biodiesel, ethanol and diesel blends for diesel engine applications with engine emission profile. *Fuel*, 319, 123798, 2022. https://doi.org/10.1016/j.fuel.2022.123798

[57] *Zuo, L., Wang, J., Mei, D., Dai, S., &Adu-Mensah, D*Experimental investigation on sdiesel engine using partially hydrogenated biodiesel-ethanol-diesel ternary blend. *Renewable Energy*, 185, 1272-1283, 2022. https://doi.org/10.1016/ j.renene.2021.12.085

[58] *Bhargavi, M., Kumar, T. V., Shaik, R. A. A., Kanna, S. K., & Padmanabhan, S*. Effective utilization and optimization of waste plastic oil with ethanol additive in diesel engine using full factorial design. *Materials Today: Proceedings*, 52, 930-936, 2022. https://doi.org/10.1016/j.matpr.2021.10.310

[59] *Swamy, L. R., Banapurmath, N. R., Harari, P. A., Chandrashekar, T. K., Keerthi, B. L., Hemanth, C., ... & Kulkarni, P. S.* Diesel engine performance fuelled with manifold injection of ethanol and water-in-diesel emulsion blends. *Materials Today: Proceedings*, 2022. https://doi.org/10.1016/j.matpr.2022.05.419

[60] *Chuepeng, S., Pirompugd, W., &Sutheerasak, E.* Performance and emissions of a diesel engine fueled with palm oil ethyl ester combined with fumigated ethanol on a dual fuel mode. *Energy Reports*, 9, 470-477, 2023. https://doi.org/10.1016/j.egyr.2022.11.067

[61] *Rao, D. N., & Reddy, A. S.* Effects on the performance and emission characteristics of CRDI diesel engine fueled with ethanol, acid oil methyl ester biodiesel and diesel blends. *Materials Today: Proceedings*, 2023. https://doi.org/10.1016/ j.matpr.2023.06.065+9s

[62] *Kurre, S. K., Yadav, J., Khan, M. K., Yadav, P., Dhebar, M. M., & Rawat, B. S.* Experimental evaluation of performance and emission of diesel engine fueled with nano-material titanium dioxide (TiO2) nanoparticles supplemented diesel-biodiesel-ethanol blends. *Materials Today: Proceedings*, 2023. https://doi.org/10.1016/ j.matpr.2023.01.306

[63] *Kharkwal, V. S., Kesharvani, S., Verma, S., Dwivedi, G., & Jain, S.* Numerical investigation of engine characteristics of a diesel engine fuelled with ethanol and diethyl ether supplemented diesel-WCO biodiesel blend. *Materials Today: Proceedings*, 2023. https://doi.org/10.1016/j.matpr.2023.02.106

[64] *Nagwan, H., Bangari, R. S., Singh, K., & Kumar, P.* Study the performance characteristics of CI engine with hemp oil methyl Ester, ethanol and diesel blends. *Materials Today: Proceedings*, 2023. https://doi.org/10.1016/ j.matpr.2023.05.108

Conflict of Interest

The authors affirm that they have no known financial or interpersonal conflicts that may have looked to have influenced the research presented in this study.

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