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COMPREHENSIVE REVIEW OF ORGANIC ADDITIVES PROPERTIES AND THEIR EFFECTS ON CHARACTERISTICS OF PERFORMANCE AND EMISSIONS IN DIESEL ENGINES

Summary. Recently, organic additives have shown an essential role in improving fuel quality, promoting combustion efficiency, and minimizing pollutants. This research examines the properties and effects of several organic compounds on the performance and emission characteristics of diesel engines. The review results emphasize its impact on engine performance parameters, including power production, thermal efficiency, and fuel economy, as well as decreases in emissions of particulate matter, nitrogen oxides, and hydrocarbons. Challenges of optimizing additives and progress in cleaner combustion technologies are discussed. This study also demonstrates different suggested mechanisms for organic additives effect on

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engine performance and environmental sustainability; moreover, future research directions are introduced.

Keywords: diesel fuel, organic additives, engine performance, emissions, diesel engines

1. INTRODUCTION

The globalized world, advancing technology, and increasing population have resulted in the quick depletion of high-energy and non-renewable energy sources, particularly fossil fuels [1]. Diesel fuel is among the most extensively utilized fuels for transportation and industrial purposes due to its efficiency and energy density. Nonetheless, it presents numerous obstacles, including elevated emissions and performance issues under specific conditions [2].

Over the years, researchers have been investigating numerous methods to enhance diesel fuel performance and mitigate its environmental impact, including engine design modifications, exhaust treatment devices, and fuel additives [3]. The utilization of additives is among the most promising solutions. Additives are chemical compounds incorporated into fuel in minimal concentrations to enhance, preserve, or provide advantageous properties to the basic fuel. Additives are often classified into two categories: organic and inorganic [4].

Many researchers have employed organic additives that consist of hydrogen-carbon chains [5]. In the 1980s, researchers started studies in this field using alcohol-based additives and showed that ethanol-diesel blends are possible for diesel engines [6]. Subsequently, many other organic compounds were employed by several researchers [4].

Fig. 1. shows the overall number of papers that were published in the last twenty years, as per the Scopus tool, and related to the usage of organic compounds in diesel engines by several researchers. The majority of research work has occurred in the past decade, with sustained interest in this topic.

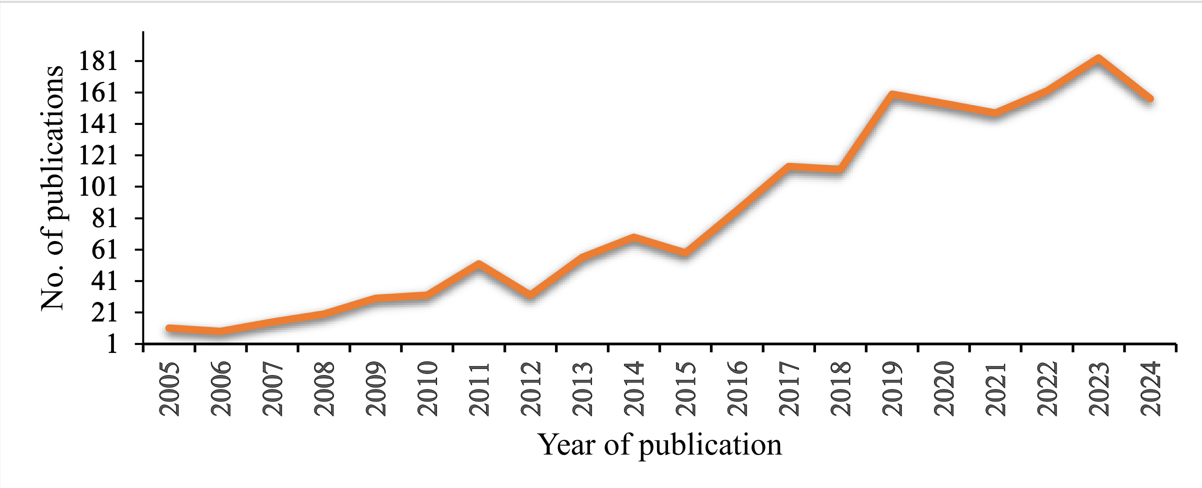

Fig. 1. A statistic indicates the quantity of articles over the past two decades on organic additives in fuel

This study aims to do a thorough evaluation of the physicochemical features of organic additive-diesel blends that influence the performance and emission characteristics of compression ignition (CI) engines. Moreover, it highlights the challenges that must be addressed before the extensive adoption of these additives in cleaner fuels and more sustainable transportation systems. This study categorizes organic additives and demonstrates their impact on diesel engine performance, whether utilized separately or in combinations at varying doses. This review may serve as a valuable resource for researchers seeking to develop novel combinations of additives that improve engine performance while simultaneously reducing emissions.

2. PHYSICOCHEMICAL PROPERTIES OF ORGANIC FUEL ADDITIVES

Considering the physicochemical features of fuel additives is essential for evaluating the behavior of fuel blends. These properties provide insights into the mixture's quality and combustion attributes, involving ignition quality, ignition delay, and flame propagation during combustion [4]. Tab. 1 presents a set of previously published physicochemical properties of several organic additives compared to neat diesel fuel.

Tab. 1

Physicochemical characteristics of several organic additives in regard to diesel fuel

Type	Additive	Density (kg/m^3)	Latent heat (kJ/kg)	Boiling point (°C)	Cetane number	Oxygen content (%)	Lower heating value (MJ/kg)	Auto-ignition temperature (°C)	References
	Diesel ($C_{12}H_{23}$)	840	260	185–345	51	0	42.5	316	[17]
Alcohols	Methanol (CH_3OH)	796	1109	64.5	3	50	19.9	470	[8]
	Ethanol (C_2H_5OH)	790	904	78.4	8	34.8	26.8	434	[8]
	n-Butanol (C_4H_9OH)	810		117.7	12	21.6	33.1	343	[9]
	n-Pentanol ($C_5H_{11}OH$)	814.8	308		20 - 25	18.1	34.65		[10]
Ethers	DME (CH_3OCH_3)		461	−24.9	55 - 65	34.8	27.6	350	[11]
	DEE ($C_4H_{10}O$)	713	350		125	21.6	33.9	380	[12]
	MTBE ($C_5H_{12}O$)		340	328.2	6	18.2	35.2	698	[13]
	ETBE ($C_6H_{14}O$)	747		71.7	2.5		37.9		[14]
	$PODE_3$ $H_3CO(CH_2O)_3CH_3$	1020			78	47.1	19.1		[15]
	$PODE_4$ $H_3CO(CH_2O)_4CH_3$	1070			90	48.2	18.4		[15]

	DPE ($(C_6H_5)_2O$)	1073		258		10.12			[16]
Aromatics	DMF (C_6H_8O)	890	333	92- 94	9	16.7	33.7	285.8	[17]
Nitro-Paraffins	NM (CH_3NO_2)	1138	561	162		52.4	10.52	418	[18]
	NE ($C_2H_5NO_2$)	1045	490	100 - 103		42.6	18.1	414	[18]
Esters	DMC ($CH_3OCOOCH_3$)	1075		90 - 91	35 - 36	53.3	15.78		[19]
	EGM ($C_4H_8O_3$)	1009			0.1				[20]
	EE ($C_4H_8O_2$)	899–902	404	76–77	10	36.4	23.7	426	[21]
	MEA ($C_5H_{10}O_3$)	1010		145		40.7	21.1	392	[19]
	EEA ($C_6H_{12}O_3$)	975			61	16.7	23.57		[22]

Every property of a fuel additive significantly influences the combustion process of the fuel mixture. Consequently, it is necessary to properly evaluate the subsequent factors when choosing additives for base diesel fuel based on the following recommended notes [23]:

- In comparison to diesel, additives with lower viscosity and density enhance the pumping of additive-fuel mixtures and contribute to their stability and solubility.
- It is advantageous for the chosen additives to have a boiling point similar to that of diesel and a lower auto-ignition temperature.
- Additives having higher cetane numbers and oxygen concentrations are favored, as they enhance the combustion of the fuel, thus reducing the probability of knocking.
- Additives with less latent heat can enhance the process of combustion by facilitating quicker and more efficient fuel blend ignition. But the majority of organic additives generally possess a latent heat value superior to that of diesel.
- Additives lower heating value should surpass that of diesel fuel. A low value of this property may result in higher specific fuel consumption. Consequently, the financial issue should be taken into consideration while choosing an additive.

3. IMPACT OF ORGANIC ADDITIVES ON ENGINE PERFORMANCE AND EMISSIONS

The performance of an engine, determined by measurements such as Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumption (BSFC), along with its emissions, including smoke, soot, Unburned Hydrocarbons (UHC), Nitrogen Oxides (NO_x), Particulate

Matter (PM), Carbon Monoxide (CO), and Carbon Dioxide (CO_2), depends on several design and operating variables. Variables include injection timing, compression ratio and pressure, fuel dilution with additives, exhaust gas recirculation (EGR), engine load, and engine speed [4]. However, significant changes to design parameters are frequently constrained by the standardized and complicated nature of engine designs, which cannot be modified beyond a certain level. In the past two decades, there has been an increasing emphasis on research investigating modifications to these parameters, especially concerning fuel blending ratios, to enhance engine performance and emissions [4]. Additives are basically utilized in diesel fuels to improve engine performance, diminish emissions, enhance fuel efficiency, optimize combustion rates, and promote the protection of the environment. They also enable fuels to perform under extreme conditions and act as antioxidants [8]. However, Khalife et al. [26] concluded that while additives can enhance combustion, they should not be considered a universal solution for all scenarios. They conducted a review to evaluate the impact of additives on engine performance and emissions during steady-state operation.

Organic additives have gained considerable interest owing to their enhanced combustion characteristics relative to pure diesel fuel [4].

The following discussion examines the effects of the most common organic additives utilized with diesel fuel on engine performance and emissions.

3.1 Alcohol Additives

Alcohol is an organic molecule characterized by the presence of more than one hydroxyl (-OH) chemical group bonded to a saturated carbon atom. The addition of a hydroxyl group dramatically modifies the properties of hydrocarbons, providing hydrophilic attributes [27].
Alcohol-based additives are oxygen-rich fuels that can enhance combustion efficiency and reduce emissions [28]. This is, somehow, consistent with Khalife et al. [26] who indicated that blending alcohols (in volumes below 10%) with diesel enhanced critical performance parameters such as BTE and BSFC, and lowered PM and HC emissions owing to enhanced oxygen availability in the combustion zone. However, it was noted that CO and NO_x emissions tended to increase. Adelman and Wagner et al. [29] explained that alcohols have a lower viscosity than pure diesel, allowing them to be more easily atomized, injected, and mixed with air during the combustion process. While C.T. Chong et al. [30] emphasized that alcohols show a higher laminar flame propagation speed, generally between 0.45 to 0.55 m/s, in contrast to diesel's 0.45 m/s at an equivalence ratio of 1. The increased flame speed facilitates a more rapid combustion process, hence improving engine thermal efficiency. Pan et al. [31] clarified that alcohols have a high latent heat of vaporization, which provides significant evaporative cooling and lowers the intake charge temperature during combustion. This phenomenon improves the engine's volumetric efficiency and reduces the work needed throughout the compression stroke. In addition, alcohols decrease emission levels owing to their high oxygen content, which facilitates cleaner burning. Their elevated stoichiometric air-fuel ratio, minimal sulfur content, and high hydrogen-to-carbon ratio improve combustion efficiency and diminish hazardous emissions. Alptekin [32] found that alcohol mixtures had no major effect on CO_2 emissions.

3.1.1 Methanol

Methanol is considered a renewable, inexpensive, and environmentally friendly alternative to traditional fossil fuels [33]. Recently, many researchers have explored using methanol as a substitute for conventional fuels in diesel engines to ensure economic and environmental issues. Lijiang [7] studied the impact of different methanol/diesel ratios on engine performance and emissions, and noted that mixing a small amount of methanol into diesel did not greatly affect BTE. However, increased methanol concentration resulted in a slight decrease in BTE. With the rise in methanol concentration, emissions of soot and NO_x reduced; however, emissions of UHC and CO increased. Mustafa Vargün [8] analyzed the results of methanol/diesel and ethanol/diesel blends in comparison to pure diesel fuel. The utilization of M20% fuel mixture greatly enhances BTE values. Utilizing M20% and E20% fuels resulted in NO_x emissions that were typically higher than that of pure diesel fuel. Huang [34] conducted an investigation on a diesel engine using methanol/diesel blends, demonstrating that a rise in methanol percentage in the fuel blend resulted in enhanced BTE and reduced BSFC. The enhancement was attributed to the higher proportion of premixed combustion, enriched oxygen content, and advancements in the diffusive combustion phase. The research noted substantial decreases in smoke and CO emissions, no alterations in UHC emissions, and an increase in NO_x emissions. Wang [35] studied the impact of intake air temperature on the emissions and performance parameters of a methanol/diesel fuel. It was observed that emissions of UHC, CO, unburned methanol, and formaldehyde increased with the rising proportion of fumigated methanol. However, these unregulated emissions diminished when the intake air temperature increased. Lijiang Wei [36] examined the impact of methanol fumigation on a turbocharged, intercooled diesel engine and observed an increase in CO and UHC emissions (which were reduced by using Diesel Oxidation Catalyst). In contrast, NO_x and soot emissions were significantly decreased. Sayin [37] analyzed the emission outcomes of the original against advanced injection timing. They noted an increase in NO_x and CO_2 emissions; however, smoke opacity, UHC, and CO emissions decreased with retarded injection timing.

3.1.2 Ethanol

Ethanol, a fuel that can be generated from biomass, may be synthesized from several plant materials, and weak cereal grains, including corn, wheat, rice, barley, and similar sources, serve as excellent substrates for ethanol production [38]. Ethanol has a lower boiling point than diesel, resulting in its earlier evaporation. Once diesel ignites, the unburned ethanol can facilitate the continuation of the combustion process [39]. Yage [40] used ethanol/diesel blends, yielding a low improvement in BTE alongside increases in UHC, CO, and NO_x emissions. Arifin [41] employed bioethanol/diesel blends, resulting in reduced CO and smoke emissions, while NO_x emissions increased. Chen et al. [42] found that BSFC increased while emissions decreased with larger ethanol concentrations (smoke and UHC); however, NO_x emissions remained constant or minimally increased with fuel blends compared to pure diesel. Gvidonas found that ethanol/diesel blends reduce density, viscosity, carbon-to-hydrogen ratio, and flash point and enhance volatility and oxygen content in the fuel mixture. This modification increases air-to-fuel ratio in fuel-rich zones, facilitates complete combustion near stoichiometric conditions, and reduces exhaust smoke [43]. The idea of adding different additives at a time shows promising results; for example, the optimal blend of DEE-diesel was determined to be 10% DEE and 10% ethanol with diesel, resulting in a 15.94% increase in (BTE). Furthermore, emissions were reduced (PM-91%, CO-53.14%, and NO_x) in comparison to diesel [12].

3.1.3 N-butanol

Research results indicate that n-butanol can overcome problems associated with methanol and ethanol. Its enhanced fuel characteristics, including an elevated cetane number, improved miscibility, advantageous oxygen-to-hydrogen and oxygen-to-carbon ratios, and increased heat capacity, enable a reduction in emissions without compromising engine power output [44]. Rakopoulos [27] noted that NO_x emissions from butanol/diesel blends are marginally lower than those from the same case of pure diesel fuel. This may be attributed to the engine operating in a generally 'leaner' manner, with the temperature-reducing effect of butanol exerting a predominant influence, countered by the lower cetane number of butanol potentially resulting in elevated temperatures during the premixed phase of combustion. Optical analyses revealed that butanol blends facilitated accelerated production and increased concentration of OH in the combustion chamber, which prompted an acceleration in the soot oxidation phase [45]. Using butanol-blended fuel requires a larger amount of fuel to achieve equivalent engine performance. The increase in torque and power for BU5% is attributed to combustion enhanced by the oxygen component of butanol, whereas the reduction for BU10% and BU20% is mostly due to butanol's reduced heating value relative to pure diesel fuel [46]. Sahin [47] used n-butanol/diesel fuel blends at lower volumetric ratios (2%, 4%, and 6%) aiming to reduce additive costs. They noted different results in BSFC, BTE, and NO_x, and a reduction in smoke and UHC emissions across all blends. Nayyar [48] suggested that engine performance may be improved through the utilization of a butanol-diesel blend, contingent upon appropriate variable factors such as injection timing, injection pressure, and compression ratio. Toxic emissions can be reduced by employing a butanol/diesel blend with appropriate variable conditions in the engine [9]. Haozhong noted that adding $PODE_{3\text{-}4}$ to n-butanol/diesel fuel mixtures enhanced combustion efficiency and diminished pollutants. Incorporating n-butanol into diesel fuel leads to a little reduction in maximum in-cylinder pressure and heat release rates [49]. Xiuzhen Li [50] discovered that adding n-butanol to the diesel engine extended the delay period, increased the quantity of premixed combustion, and reduced the combustion duration. Murat [51] used isobutanol/diesel fuel mixtures. Their results indicate an increase in BSFC and UHC emissions, alongside a reduction in brake power (BP), BTE, CO, and NO_x emissions.

3.1.4 N-pentanol

Many investigations have been conducted on short-chain alcohols, including ethanol and methanol, as additives for the suggested replacement fuel in CI engines. Nevertheless, longer-chain alcohols such as n-butanol and n-pentanol are receiving increasing attention from frequent studies for usage as fuel in CI engines [52]. N-pentanol exhibits superior fuel characteristics compared to ethanol, methanol, and butanol [53]. Due to its superior miscibility with diesel and vegetable oils, n-pentanol has recently emerged as a preferred option among researchers [52]. Kumar discovered that pentanol/diesel blends enhanced BTE and BSFC while simultaneously reducing CO, UHC, and NO_x emissions upon the addition of methyl ester fish oil (MEFO) [52]. Moshen found that the addition of pentanol into diesel fuel led to elevated CO and UHC emissions while reducing soot due to the presence of DME [10].

It can be observed that the oxygen content in alcohols improves combustion quality and increases BTE; they affect NO_x emissions in contradictory ways, and the major effect of them on UHC and CO emissions has the same behavior, whether resulting in an increase or decrease in both of them.

3.2 Ethers Additives

Ethers' ability to establish hydrogen bonds with other compounds makes them highly effective solvents for several chemical molecules [54]. Due to the inability of ether molecules to participate in hydrogen bonding among themselves, they exhibit significantly lower boiling points compared to alcohols of comparable molecular weights [54]. A potential method to enhance the compatibility of diesel with ethanol is the utilization of ethers, like ethyl ter-butyl ether (ETBE) and ter-amyl ethyl ether (TAEE). These ethers are semi-renewable chemicals synthesized from the interaction of isobutene and isoamylenes (2-methyl-butene-1 and 2-methyl-butene-2) with ethanol [55].

3.2.1 Dimethyl ether (DME)

Adding DME pre-mixing ratio in the blend may improve engine performance by increasing both the pressure and temperature inside the engine cylinder via homogeneous charge combustion, resulting in a diminished ignition delay period and enhanced evaporation of the blend [11]. The addition of DME delays injection timing and reduces the equivalence ratio, resulting in decreased in-cylinder pressure, hence generating fewer NO_x emissions [56]. Xiuzhen Li [50] noted that adding DME to diesel fuel leads to a reduction in NO_x and soot emissions. Wang [57] found that DME/diesel blends increased BSFC in order to compensate for DME's lower calorific value and density. The low boiling point of DME requires a pressurized system to keep the fuel in a liquid form.

3.2.2 Diethyl ether (DEE)

The DEE is a biofuel, generated from ethanol by a dehydration process with acid catalysts [58]. A significant concentration of DEE (≥ 30% by vol.) in blended fuel may severely knock in the engine [59]. Paul performed research utilizing two blends of DEE/diesel fuel (DEE 5% and DEE 10% by vol). BTE of the engine improved with DEE 5% but declined with DEE 10%. While brake-specific energy consumption (BSEC) decreased with DEE 5%, each further rise in DEE percentage increased the BSEC of the engine. The addition of DEE in diesel fuel reduced the emissions of PM, CO, HC, and NO_x at a concentration of 10% DEE; however, NO_x emissions increased with DEE 5% [12]. Ibrahim experimentally observed that the addition of DEE as a fuel additive considerably enhances engine performance across various load conditions. The highest BTE (7.2%) and the lowest BSFC (6.7%) were attained with a DEE concentration of 15% in diesel fuel, in contrast to pure diesel [60]. Kapilan noted that the addition of DEE leads to reduced smoke emissions and increased NO_x emissions [61]. Patil noted that adding DEE to diesel fuel leads to reduced NO_x emissions [62]. CO emissions were reduced with higher DEE concentrations ranging from 5% to 15% across all load conditions. Furthermore, increasing DEE blends enhanced mechanical efficiency across all load levels [63].

3.2.3 Methyl tertiary-butyl ether (MTBE)

A significant issue that impeded the utilization of MTBE as an effective gasoline additive is its comparatively high solubility in water. It can be solved by following a detailed azeotropic mixture in which only one homogenous phase exists [64]. Murari Roy [65] used 5% MTBE with diesel fuel and noted lower formaldehyde (HCHO) emissions. Awad et al. [66] found that adding MTBE to fuels such as diesel and biodiesel leads to elevated oxygen content, altering engine output conditions. Furthermore, it is proposed that MTBE may be used in high-power-rating engines with a variable compression ratio according to its characteristics. M. Roy [13] noted that a 5 vol.% addition of MTBE to diesel fuel reduced HCHO emissions, attributable to superior mixture formation and combustion due to the blend's lower boiling point and oxygen content. The 10 and 15 vol.% MTBE blends result in an excessively lean mixture due to their low boiling point, which eliminates the beneficial impact of their O_2 concentration, hence worsening exhaust odor and emissions. Furthermore, there is an increase in UHC emissions associated with the addition of MTBE.

3.2.4 Ethyl tert-butyl ether (ETBE)

The production of ethyl tert-butyl ether (ETBE) involves the reaction of a mixture of bio-ethanol and isobutene with heat in the presence of a catalyst. As a "biofuel," ETBE contributes to the reduction of carbon dioxide emissions from vehicles, a greenhouse gas released into the environment [14]. ETBE has low auto-ignitability, a low boiling point, and exhibits limitless solubility in diesel fuel. Consequently, ETBE, when utilized as an addition in diesel fuel, can mitigate smoke emissions that increase with exhaust gas recirculation (EGR) and to prolong smokeless and low-NO_x diesel combustion at elevated loads by enhancing fuel-air mixing and leveraging its oxygenated characteristics. Tie Li used ETBE/diesel fuel blends and noted a reduction in smoke alongside an increase in NO_x emissions [14]. Reduced cetane numbers in ETBE/diesel fuel blends result in higher fuel consumption and a higher percentage of UHC, potentially affecting combustion characteristics and environmental emissions [55].

3.2.5 Polyoxymethylene dimethyl ether ($PODE_n$)

PODE's combustion performance may be enhanced, and particulate emissions for diesel engines may be significantly reduced due to its high cetane number, high oxygen content, and absence of aromatic hydrocarbons and sulfur. Nevertheless, its low flash point and low heating value present obstacles to fuel efficiency and transportation and storage safety [67]. The viscosity and distillation ranges of PODE are lower than those of diesel fuel [68]. Liu et al. [69] used 10% and 20% by volume PODE/diesel, revealing that PODE considerably reduced UHC and soot emissions. Lin et al. [70] investigated PODE3/diesel mixtures (0–30 vol%) and discovered that the incorporation of 10% PODE3 results in a reduction of both large-size and ultrafine particles in comparison to pure diesel. Junheng [71] the addition of 30 vol% PODE can reduce particulate emissions by up to 47.6% in comparison to the diesel case. Qiren observed that the addition of PODE can prolong the ignition delay and shorten the duration of combustion. The duration of combustion and the delay of ignition can be reduced by increasing the injection pressure. The inclusion of PODE can reduce UHC emissions, with PODE4/diesel being the most effective. At the same time, the implementation of PODE has the potential to slightly reduce NO_x emissions. $PODE_3$/diesel and $PODE_4$/diesel exhibit similar efficacy in diminishing NO_x emissions [15]. The influence of PODE is not noticeable at low loads, since oxygen availability is adequate due to the elevated air/fuel (A/F) ratio; combustion temperature is the primary determinant. At full load, the reduced A/F ratio reveals the effect of PODE on NO_x emissions [71]. The blending of PODE with diesel increased the BTE of the engine somewhat due to the greater cetane number, shorter ignition delay period, and faster combustion rate of PODE [72]. The addition of PODE is seen to diminish CO and UHC emissions while elevating NO_x emissions [73].

3.2.6 Diphenyl ether (DPE)

Srihari [16] used DPE/diesel blends supplemented with Diethyl Amine (DEA) as an antioxidant compound. The results indicate a reduction in UHC and smoke emissions, as well as a drop in NO_x emissions, attributable to the incorporation of DEA.

It is noted that the major effect of ethers on UHC and CO emissions takes the behavior of decreasing them; both smoke and soot are found to be reduced by them, and they have different effects on NO_x emissions.

3.3 Aromatics Additives

Aromatics are organic substances characterized by a planar, unsaturated ring of atoms stabilized through bond interactions within the ring. Common aromatic additives include toluene and dimethyl furan (DMF), etc. [74]. Recent investigations have identified 2,5-dimethylfuran (DMF) as a viable biofuel additive for diesel. Previously, DMF garnered limited interest from researchers due to challenges in its synthesis. Nonetheless, various researchers' substantial advancements in production methodologies have rendered it suitable for widespread use as automotive engine fuel [75]. Using DMF/diesel blends alongside moderate EGR may be a superior option for diesel engines to meet upcoming emission regulations while maintaining high fuel efficiency [76]. Guisheng [17] found that DMF addition has small effects on NO_x, UHC, CO emissions, and BSFC. It had a great effect on reducing soot emissions [77]. Mingrui used DMF/diesel fuel blends and found that results show an increase in BTE and a decrease in BSFC [78].

It can be clearly verified that aromatics have a significant effect on reducing soot emissions.

3.4 Nitro-paraffins Additives

The combustion characteristics, including flash point and cetane number, may be enhanced by the high oxygen content of the molecular structure of nitroparaffins. Nitro-paraffin compounds are primarily composed of nitromethane (NM) and nitroethane (NE)., among others. The atomization and spray quality of the blended fuel are enhanced by NE and NM, which may facilitate the attainment of a higher BTE [18]. Moghaddam found that the reduction in smoke value was found to be 35.7% and 16.2% using 10% NE and NM, respectively [18]. The use of NE in the fuel combination resulted in a 44% reduction in smoke value; however, NO_x levels increased [79].

So, nitro-paraffins had the effect of BTE improvement and reduction of smoke emissions.

3.5 Esters Additives

Ester compounds result from an esterification reaction between a carboxylic acid and an alcohol. Its oxygen-rich composition may contribute to the reduction of emissions. Common examples of ester compound additions are 2-ethoxy ethyl acetate (EEA), 2-methoxy ethyl acetate (MEA), and ethylene glycol monoacetate (EGM), among others [4].

3.5.1 Dimethyl carbonate (DMC)

Although the maximal heat release rate of the DMC/diesel blend exceeded that of pure diesel, the combustion point of the blend was slightly delayed due to the lower cetane number of the DMC than that of diesel [50]. Mingzhang discovered that adding DMC diminishes soot and particulate matter emissions. DMC decreases soot emissions by approximately 60% [80]. The addition of 10% DMC into diesel fuel clearly decreases UHC and CO emissions. The increase in NO_x emissions can be attributed to the incorporation of the oxygenated fuel DMC; however, this increase is modest when compared with the reduction of engine load [81]. Cheung observed that as DMC increases, CO rises at low to medium engine loads but drops at high engine loads. UHC undergoes a minor decrease, NO_2 increases, and the variation in NO_x is not statistically significant. Cheung also discovered a rise in BSFC. Nonetheless, enhancements in the combustion process result in a minor increase in BTE [82].

3.5.2 Ethylene glycol monoacetate (EGM)

EGM can be synthesized by heating ethylene glycol with glacial acetic acid or acetic anhydride or by introducing ethylene oxide into heated acetic acid containing sodium acetate or sulfuric acid [20]. Lin used EGM/diesel blends and found that BSFC increased as the EGM content in diesel increased, while the exhaust gas temperature, excess air, and NO_x decreased. Conversely, CO and CO2 increased in comparison to pure diesel [20].

3.5.3 Ethyl Ethanoate (EE)

Ethyl ethanoate and other esters possess numerous advantageous attributes, such as a high oxygen content, considerable miscibility with diesel, low kinematic viscosity, and a high auto-ignition temperature [83]. Shadrack discovered that the results indicate a decrease in BSFC and NOx emissions and an increase in CO emissions as a consequence of varying concentrations of EE [21].

3.5.4 Methoxyethyl acetate (MEA)

MEA is produced as a diesel additive based on the following principles: firstly, it can be easily mixed with diesel; secondly, there are enough sources for synthesis; and thirdly, there is minimal alteration in the fuel delivery system, engine performance, and fuel efficiency. Furthermore, MEA has the following advantages: its boiling point is the closest to that of diesel fuel, high-energy density, and good solubility with diesel [19]. Gongmused used MEA/diesel blends and found a decrease in BP, CO, UHC, and smoke emissions [19].

3.5.5 Ethoxyethyl acetate (EEA)

The use of EEA/diesel blends resulted in an improvement of BTE and higher BSFC, while decreasing Smoke, CO and HC, and increasing NO_x emissions [84].

It can be noted that the oxygen content of esters decreases CO and UHC emissions, and they have contradictory effects on NO_x emissions like alcohols and ethers.

Tab. 2 summarizes the effect of organic additives on diesel engines performance and emissions.

Tab. 2

Summary of the results of the previous research

Category	Organic Additive		Engine specification	Engine Performance			Emission						References
	Name	Conc. %		BTE	BSFC	BP	CO	CO_2	UHC	Soot	NO_x	Smoke	
Alcohols	Methanol	Up to 20%	6 cyl., CRDI	↓			↑		↑	↓	↓		[7] 2016
		20%	4 cyl., CRDI	↑	↓			↓10 %			↑		[8] 2022
		Up to 20%	6 cyl., CRDI				↓		↓	↓	↓		[36] 2015
		5,10,15%	1 cyl., DI	↓	↑		↓5:22 %	↑14:68 %	↓33:52%		↑22:69%	↓26:50%	[37] 2009
		Up to 30%	4 cyl., CRDI				↑		↑	↓			[85] 2017
	Ethanol	20%	4 cyl., CRDI					↓10 %	↓20 %		↑		[8] 2022
		10%+10% DEE	1 cyl., DI, VCR	↑			↓		↓	↓	↓		[12] 2015
		15%	4 cyl., CRDI		↑ 6%		↑ 16		↑		↑7 %		[32] 2017
		4%	VCRE	↑	↓								[39] 2002
		6,18,24 %+1-Decano	4 cyl., DI	↑			↑		↑		↑		[40] 2009
		5%+1% Emuls.	2 cyl., IDI									↓	[41] 2015
		10% +1% Emuls.					↓				↑	↓	
		10,20, 30 % + FAME(5,10,15 %)	4 cyl.				↓		↓		↑	↓	[42] 2008
		15% + 5% RME	4 cyl., DI		↑		↓		↓		↓	↓	[43] 2014

		10%+1 %Isop.	4 cyl., DI			↓12 %	↓				↑	↓	[86] 2004
		15%+1 %Isop.				↓20 %	↓				↑	↓	
	N-butanol	20% +EHN	1 cyl., CRDI							↓			[9] 2013
		10,15, 20 %	1 cyl., DI		↑		↑				↓		[21] 2023
		8,16,24 %	1 cyl., DI	↑	↑		↓		↑		↓	↓	[27] 2010
		20%	4 cyl., CRDI								↓	↓	[45] 2014
		20%	4 cyl., CRDI		↑ 3%		↑		↑		↓		[46] 2015
		2%	4 cyl., CRDI	↑	↓			↑	↑24 %		↓	↓	[47] 2015
		4%		↓	↑			↑	↑31 %		↑	↓ 21%	
		6%		↓	↑			↑	↑29 %		↑	↓	
		20%	1 cyl., DI, VCR E	↑ 5 %							↓	↓	[48] 2017
		20%	4 cyl., DI							↓			[49] 2017
		20%+ PODE3-4 (10,20		↑	↑		↓		↓	↓	↑		
		30% by mass	4 cyl., CRDI							↓ 85 %	↓ 0.5 %		[50] 2024
		Iso-butanol 5,10,15 ,20%	1 cyl., DI	↓	↑	↓	↓		↑		↓		[51] 2009
	N-pentanol	20% +20% DME	4 cyl., CRDI		↑		↑		↑	↓	↓32 :56 %		[10] 2019
		10%+ MEFO(20,30%)	1 cyl., DI	↑	↑		↓		↓		↓		[52] 2020

Ethers	DME		2 cyl.				↑		↑		↓	↓	[11] 2014
		18.6% by mass	4 cyl., CRDI							↓ 32 %	↓ 1.7 %		[50] 2024
		10,15,20% by mass	4 cyl., DI				↑		↑		↓	↓58 :68 %	[57] 2008
	DEE	5%	1 cyl., DI, VCR	↑	↓		↓		↓	↓	↑		[12] 2015
		10%		↓	↑		↑				↓		
		10,25, 50% by mass	1 cyl., CRDI				↓		↓	↓	↑		[59] 2017
		15%	1 cyl., DI	↑ 7 %	↓ 6.7 %								[60] 2016
		5%	DI	↑			↓		↓		↑	↓	[61] 2008
		2,5,8, 10,15%	1 cyl., DI	↑	↑		↓		↑		↓	↓	[62] 2015
		5,10,15 ,20%	1 cyl.	↑	↓		↓		↓		↓		[63] 2024
	MTBE	5,10,15 %	6 cyl., DI						↑				[13] 2008
	ETBE	10,20, 30,40%	1 cyl., CRDI								↑	↓	[14] 2009
	$PODE_n$	18%	1 cyl., CRDI						↓		↓		[15] 2024
		10,20, 30%		↑			↓		↓	↓	↑		[67] 2022
		10,20%	4 cyl., CRDI							↓	↑		[68] 2024
		10,20, 30%	4 cyl., CRDI				↓		↓		↑	↓27, 41, 47%	[71] 2017
		20,30% by	6 cyl.	↑	↑		↓			↓	↑		[72] 2022
		20%	4 cyl., CRDI				↓		↓	↓	↑		[73] 2024
		10,20, 30%	6 cyl., CRDI	↑ 2 %			↓ 66 %		↓	↓ 76 %	↑		[87] 2021

	DPE	10,15% + 5% DEA	1 cyl., DI						↓		↓ 20 %	↓	[16] 2021
Aromatic	DMF	30%	6 cyl., CRDI							↓			[17] 2013
		10%	4 cyl., DI							↑			[76] 2017
		30%								↓			
		5,10,15 %								↓			[77] 2015
		10,30%	4 cyl., DI	↑	↓					↓			[78] 2017
Nitro-paraffins	NM	10%	4 cyl., DI	↑								↓16 %	[18] 2014
	NE	10%	4 cyl., DI	↑								↓35 %	[18] 2014
		10%	4 cyl., DI	↑						↓	↑	↓	[79] 2012
Esters	DMC	12.2% by mass	4 cyl., CRDI							↓ 8.7 %	↓ 3.3 %		[50] 2024
		20%	4 cyl., DI							↓			[80] 2019
		20% +EHN (0.5,1,2 %)		↑ 1 %	↓								
		10%	1 cyl.				↓		↓	↓	↑		[81] 2014
	EGM	5,10%	4 cyl., DI		↑		↓	↓			↓		[20] 2003
	EE	5%	1 cyl., DI				↑ 33 %						[21] 2023
		10%									↓19 %		
		15%			↓15 %								
	MEA	10,15, 20%	1 cyl., DI			↓	↓		↓			↓	[19] 2007
	EEA	5,10,15 %	1 cyl., DI	↑			↓		↓		↑	↓	[22] 2011

Explanation of abbreviations:
Conc. = additive concentration;
Cyl. = engine cylinder;
CRDI = common rail direct injection diesel engine;
DI = direct injection diesel engine;
VCRE = variable compression ratio engine;
Emuls. = emulsifier added to basic fuel;
IDI = indirect injection diesel engine;
FAME = fatty acid methyl ester;
RME = rapeseed oil methyl ester;
Isop. = isopropanol added to basic fuel;
EHN = ethyl hexy nitrate;
M 20% = (Methanol 20%+diesel 80%);
E 20% = (Ethanol 20% + diesel 80%).

4. CONCLUSION

The objective of this review study is to investigate the physicochemical properties and evaluate the impact of a variety of organic additives on the emission characteristics and performance of diesel engines. The published research can be used to draw conclusions about the efficacy of organic additive-diesel blends in comparison to diesel fuel:

- Significant enhancement in engine performance (BTE increased up to 7.2%) with minimal increase in BSFC was attained with the use of organic additives with diesel fuel.
- The oxygen content contained in all additives supports the fuel blend with oxygen. Incorporating these chemicals into diesel in suitable proportions may enhance engine performance and diminish emissions by optimizing combustion characteristics.
- Results of NOx emissions with organic compounds are contentious among researchers.
- The beneficial effect of these additions in reducing emission concentrations is not assured, as certain test results have indicated contrary behaviors. There may be an optimal dosage of a certain fuel additive to reduce emission levels.
- The analysis of the optimal performance and emission characteristics of additives-diesel ternary blends has a significant prospective extension, as there has been relatively little research conducted on the optimization of these factors. In order to enhance combustion efficiency and reduce emissions, engine parameters, such as injection pressure, compression ratio, and injection timing, may be adjusted accordingly.

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