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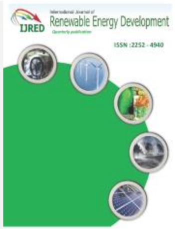

Review Article

Performance and Emission Characteristics of Diesel Engine Using Ether Additives: A Review

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Abstract. Pressure on alternative fuels and strict environmental regulations are driving a strategic shift in the efficient use of renewable biofuels. One of the promising biofuel candidates recently interested by scholars is a biological or organic additive that is added into diesel or biodiesel fuel to improve engine performance and reduce pollutant emissions. With efforts to improve efficiency and combustion quality in cylinders, combustion characteristics, flame structure and emission formation mechanism in compression ignition (CI) engines using blended fuel with organic additives have been studied on the effect of additive properties on the combustion behaviour. In this review, the physicochemical properties of typical organic additives such as ethers compounds and their effects on engine performance and emission characteristics have been discussed and evaluated based on conclusions of recent relevant literature. The results of the analysis revealed the prospect of using ether additives to improve combustion in cylinders and reduce pollutant emissions from CI engines. Obviously, the presence of higher oxygen content, lower viscosity and density, and higher cetane number resulted in a positive change in the combustion dynamics as well as a chain of mechanisms for the formation of pollutant precursors in the cylinder. Therefore, ether additives have a significant contribution to the sustainable energy strategy of the transportation sector in the next period when internal combustion engines still dominate in the competition for energy system choices equipped on vehicles.

Keywords: Ether additives; engine performance; emission characteristics; biodiesel; diesel engine.

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1. Introduction

Global warming, air pollution and the depletion of fossil fuels are raising serious concerns about the impact of the use of vehicles with internal combustion engines (Keleş, 2011)(Höök and Tang, 2013). However, reality shows that the current demand for internal combustion engines is still very large (Chau *et al.* 2020). Over 90% of the power sources in transport vehicles are spark-ignition engines and compression ignition engines (Leach *et al.*, 2020)(Atarod *et al.*, 2021). Indeed, diesel engines are still the favourite choice for transport vehicles because of their large power, high thermal efficiency, stability and reliability (Thambiyapillai and Ramanujam, 2021). However, diesel fuel contains mainly aliphatic hydrocarbons with boiling points between 130 and 370°C. As a result, emissions from diesel engines contain pollutants such as particulate emissions (PM) (Nayak *et al.*, 2020)(Ruina *et al.*, 2021), carbon monoxide (CO) (Ölçer *et al.*, 2021a)(Sivamurugan and Devarajan, 2021) and oxides of nitrogen (NOx) (Le *et al.*, 2021)(Korczewski, 2021). These pollutants can cause extreme environmental phenomena and global climate change (Nižetić *et al.*, 2020)(Nayak *et al.*, 2021). Furthermore, the applications of diesel are being tightened by strict regulations on fossil fuel use, pollution emissions, and greenhouse gas emissions engines (Viet and Tuan, 2018)(Balasubramanian *et al.*, 2021c)(Bui *et al.*, 2021). The elimination of the internal combustion engine is a long-term prospect in the future (Nguyen *et al.*, 2020)(Vo *et al.*, 2020). Nonetheless, in the short- term, there needs to be a flexible combination of effective solutions including improving engine characteristics, reducing emissions actively and passively (Vinayagam *et al.*, 2021)(Balasubramanian *et al.*, 2021a). Currently, researchers are focusing on three main solutions (Figure 1): the first is to improve the combustion process (Cao *et al.*, 2020) or optimize the engine design to meet the dual goals of

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performance and environmental protection (Tran *et al.*, 2020); the second is the use of secondary interventions through emission treatment technologies (Hoang, 2018)(Chen *et al.*, 2021b)(Trung *et al.*, 2021); third is the search for sustainable and renewable alternative fuels such as hydrogen (Bui *et al.*, 2021) and various biofuel types such as furan-based fuel (Engel *et al.*, 2021)(Ölçer *et al.*, 2021b), biodiesel (Anh, 2018), alcohol (Zeńczak and Krystosik-Gromadzińska, 2020), vegetable oils (Tabatabaei *et al.*, 2021). In addition, sustainable energy conversion, recovery and storage solutions include energy storage in flywheels (Nguyen and Hoang, 2020), waste heat recovery (Yondri *et al.*, 2021)(Anh, 2018), microbial fuel cells (Nižetić *et al.*, 2022), etc. could be potential solutions. The application of advanced engine generations or advanced emission treatment technologies may encounter economic barriers and initial investment costs (Khan *et al.*, 2015). Meanwhile, the use of renewable biodiesel fuels is attracting a lot of attention from academia to move towards reducing dependence on fossil fuels as well as proactive control of emission sources from the engine. Moreover, biodiesel is environmentally friendly, so it has been seen as a great alternative to traditional fuels. The use of biodiesel for CI engines requires minor modifications to traditional engines. Another advantage is the relatively wide and easy access to renewable fuels (Mukherjee *et al.*, 2020). In the trend of shifting biofuel production to meet global strategies for decarbonization, biofuel production from biomass is attracting much attention (Huynh *et al.*, 2021). With the aid of advanced technologies in biomass pretreatment (Chen *et al.*, 2021a) and conversion (Chong *et al.*, 2021), biorefineries have been able to produce many high value-added products with improved efficiency such as bio-alcohol (Al-Tawaha *et al.*, 2019), biodiesel, syngas, hydrogen (Arslan and Kahraman, 2021) and organic additives (Uyaroğlu *et al.*, 2021)(Nayak *et al.*, 2022).

Along with the outstanding advantages, biodiesel fuel has inherent disadvantages such as high viscosity, higher density and lower volatile characteristics compared to diesel, leading to undesirable effects on combustion behaviour (Lawan *et al.*, 2019)(Nayak *et al.*, 2017)(Le *et al.*, 2019), combustion chamber deposit formation (Le and Hoang, 2019)(Pham and Hoang, 2019a), lubrication oil degradation (Pham and Hoang, 2019b). Furthermore, the energy density of biodiesel fuels is lower than that of diesel fuel, so the specific fuel consumption may be higher (Tham *et al.*, 2019)(Hadiyanto *et al.*, 2020). In addition, the cetane number of biodiesel fuels has been reported to be lower than pure diesel fuel. That means finding an additive or chemical that can be mixed in small proportions with diesel or biodiesel fuels to give beneficial properties to the blended fuels and boost biofuel efficiency (Sezer, 2018). Current studies often classify diesel additives into two categories including organic and inorganic additives. However, organic additives are more common in biodiesel or diesel fuel applications for CI engines. The groups of organic additives can be mentioned as alcohol, ether, aromatic, aliphatic, nitro paraffin, ester. Studies in recent decades have focused a lot on evaluating the effects of alcohol additives in diesel fuel on engine characteristics, combustion characteristics and emissions (Pranesh *et al.*, 2015).

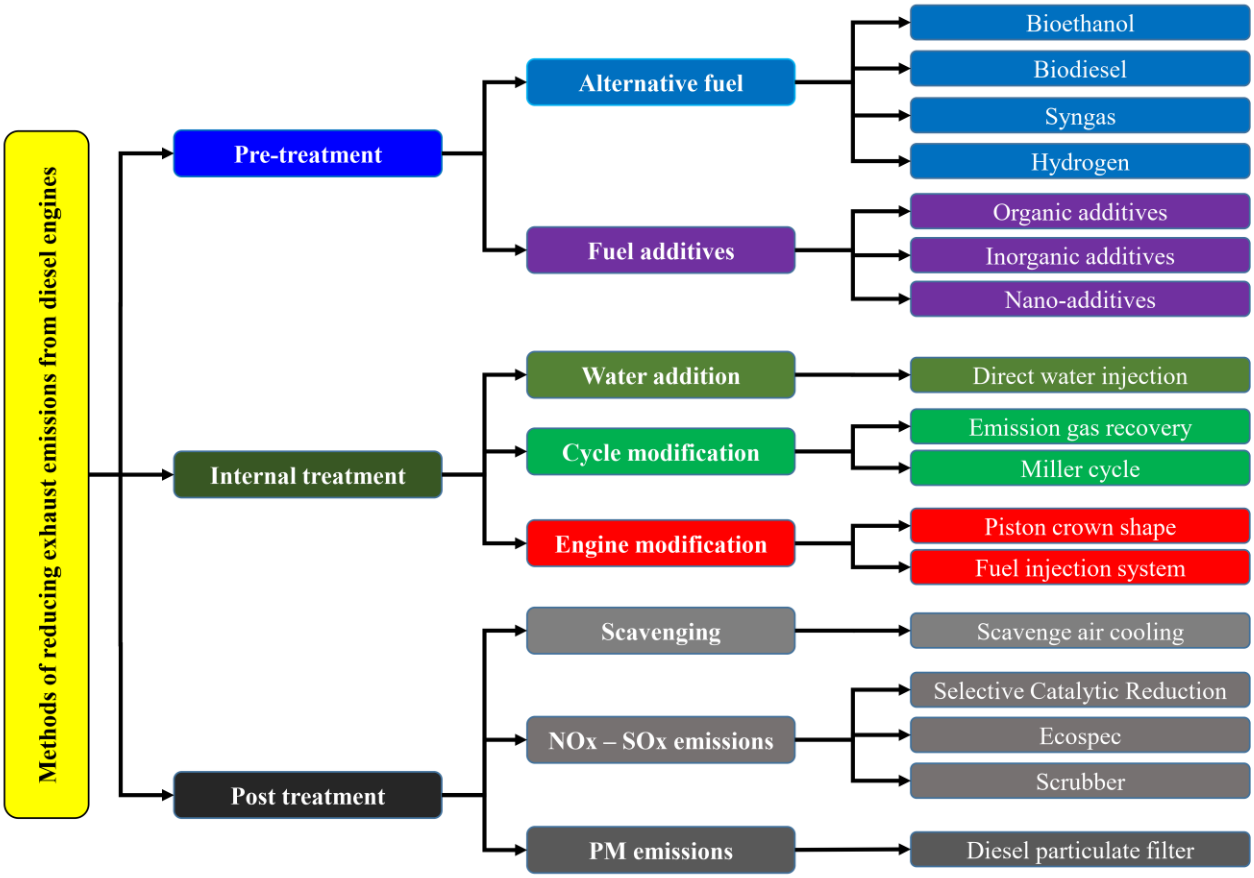

Fig. 1 Solution of reducing exhaust emission from diesel engines (Issa *et al.*, 2019)

On the other hand, the decline in global Bio-alcohol consumption during the widespread Covid-19 pandemic period led to a sharp decline in bio-alcohol refineries (Thomas *et al.*, 2021). That has accelerated the processes of converting alcohol or ethanol into more versatile and value-added products, including ethers. As for ether additives, they are increasingly making important contributions to the strategy of sustainable alternative fuel use and environmental protection (Sezer, 2020). With very high cetane numbers, some ether additives are potential additives to be added to biofuels to increase the cetane number of blended fuels (Işık *et al.*, 2020). Besides, popular ethers such as DEE and DME with low viscosity can overcome the high viscosity of biodiesel fuel to improve fuel injection quality. Recent studies have revealed that the addition of ether additives can improve important fuel properties, leading to improved combustion quality, brake thermal efficiency (BTE), brake specific fuel consumption (BSFC) and cylinder pressure (Sezer, 2019). More interestingly, blended fuels with the addition of these organic additives have provided environmental benefits by reducing emissions of PM, HCs, CO and NOx (Nižetić *et al.*, 2021c)(Morales Bayetero *et al.*, 2021).

In the past, typical organic additives have been evaluated and concluded in some basic aspects when considering their addition to conventional fuels and biofuels to supply internal combustion engines (Yetri *et al.*, 2020). However, it is difficult to find articles evaluating the physicochemical properties of ether additives as well as their impact on engine performance and emission characteristics. Therefore, in this work, brief discussions of the ether additive production pathway from biomass are firstly presented to clarify the ether additive conversion technology and characteristics before the properties of typical ether additives was investigated. More importantly, the evaluation of brake thermal efficiency, brake specific fuel consumption, exhaust temperature, brake power as well as PM, NOx, CO and HC emissions were analyzed based on published literature which demonstrated research results on the addition of ether additives into diesel and biodiesel fuels for fuelling CI engine.

2. Production of ether additives

The production of DEE can be carried out by three different methods including (1) hydration of ethylene, (2) dehydration of ethanol with sulfuric acid catalysis and (3) dehydration of ethanol with a heterogeneous catalyst. With the first process, DEE is considered as a by-product from the hydration of ethylene because the conversion of ethylene is low (4-5%) and has low DEE selectivity (Hidzir *et al.*, 2014). Therefore, this technology contributes only a small amount of DEE produced. The second method is synthesized in a gas or liquid phase reactor with ethanol to sulfuric acid ratio of 1:3, achieving a conversion efficiency of up to 95% (Chaichana *et al.*, 2019). However, the synthesis by this technique often produces acetaldehyde which makes DEE difficult to purify. The final DEE production was dehydration with heterogeneous acid catalysis such as zeolite H-Beta that converted 99% pure ethanol to DEE. If the raw material is hydrated ethanol, the resulting product still has traces of acetaldehyde, while using anhydrous ethanol, the purification of DEE is simpler because there is no acetaldehyde (Charoensuppanimit *et al.*, 2021).

There are two technological processes for the production of DME including (1) direct process using biocatalysts, synthesized from syngas with a single reactor and (2) indirect process by including a 2-step process, using methanol produced from syngas. Figure 2 shows the production of syngas from fossil fuel sources (coal, natural gas and petroleum) and biomass through steam reforming or gasification (de França Lopes *et al.*, 2020)(Cheng *et al.*, 2021). This process plays the most important role in the DME production process. The direct process has lower DME production costs due to higher CO conversion efficiency and simpler reactor construction (Yan *et al.*, 2013). However, this process produces more greenhouse gas emissions. Therefore, it is not suitable for commercial DME production.

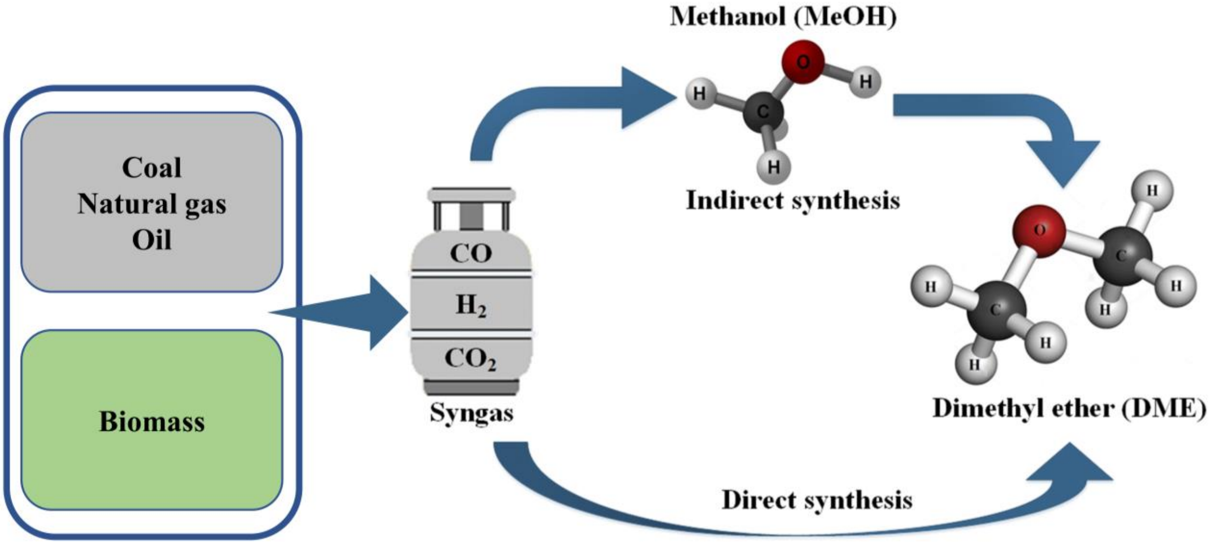

Fig. 2 The pathway of DME production (de França Lopes *et al.*, 2020)

Polyoxymethylene dimethyl ether (PODE) is usually produced through the gasification of biomass with catalytic acids with the intermediate conversion of syngas (Awad *et al.*, 2020). In particular, the process of converting PODE from methanol is that it can recycle carbon dioxide, a viable solution in the methanol economy. Besides, on the decarbonization route, PODE synthesis can be done from CO_2 and electricity. A comparative study was performed by Deutz et al. (Deutz *et al.*, 2018) of two PODE production pathways including an indirect pathway based on the combination of methanol and formaldehyde and a direct pathway based on combining CO_2 and hydrogen with catalysts. In general, recent studies on the assessment of the product life cycle of PODE have confirmed the adoption of green eco-energy, shown in Figure 3. PODE is an environmentally friendly fuel additive that can be produced from biomass (Viet and Tuan, 2021) or CO_2 (Deutz *et al.*, 2018), while the production cost is more competitive even cheaper than refining diesel from fossil resources (Aghbashlo *et al.*, 2022).

3. Properties of ether additives

For studies using alternative fuels in internal combustion engines, the physicochemical properties of modified blends have key importance in changes of the combustion and emission characteristics (Van and Anh, 2019). However, the properties of the blended fuels are highly dependent on the properties of the base fuel and fuel additives. Therefore, providing physicochemical properties of additives needs to be detailed according to each key parameter such as density, viscosity, latent heat, boiling point, cetane number, lower heat value, self-ignition temperature and oxygen content (Fayyazbakhsh and Pirouzfar, 2017). Typical properties of ether additives such as diethyl ether (DEE), dimethyl ether (DME), di-n-butyl ether (DNBE), 2-ethoxy ethyl ether (EXEE), ethyl ter-butyl ether (ETBE), 2-methoxy ethyl ether (MXEE), Ter-amyl ethyl ether (TAEE), Polyoxymethylene dimethyl ether (PODE), etc. are revealed in **Table 1**.

The cetane number is the rating assigned to diesel fuel to gauge its combustion quality. The cetane number of diesel fuel is a measure of the delay in the ignition timing of the fuel. A higher cetane number means a shorter ignition delay and complete combustion of the fuel in the combustion chamber (Yesilyurt and Aydin, 2020)(More *et al.*, 2020)(Bui *et al.*, 2020). This means that the fuel supplied to the engine has a higher cetane number resulting in a smoother running engine, better performance with more power and less harmful emissions. More interestingly, additives such as DEE (Sezer, 2011), DNBE (Kerschgens *et al.*, 2016), EXEE (Kumar *et al.*, 2018), MXEE (Ommi *et al.*, 2009) have very high cetane number values, 2-3 times higher than that of diesel fuel. The presence of these additives in the modified fuel can significantly contribute to improved combustion quality and emissions of CI engines. Furthermore, oxygen content in oxygenated additives is an outstanding advantage of ether-based additives. Additives such as DME (Zhao *et al.*, 2014) and MEA (Yanfeng *et al.*, 2007) have an oxygen content of up to 1/3 of the atomic mass, which increases the concentration of atomic oxygen in the fuels blended with the additive (Khalife *et al.*, 2017)(Sadhik Basha, 2018)(Hoang, 2021). The highest oxygen content of the ether additives was recorded as high as 47% for PODE (Barro *et al.*, 2019). Thus, the combustion quality in the cylinder is significantly improved along with the reduction of particulate emission components. For instance, a fairly common, low-cost ether compound, a potential alternative fuel candidate for CI engines, is DME that has a fairly high cetane number. It has a low self-ignition temperature so it can vaporize and burn instantly (Le *et al.*, 2021). More interestingly, with its high oxygen content, about 35% by weight of DME, while the absence of C-C bonds, it is possible to promote clean and smokeless combustion (Bauer and Kruse, 2019). Besides, with a very low boiling point, it vaporizes immediately after being injected into the cylinder, it is suitable for fuel injection pressure from 50-150MPa, so the CI engine does not need to change the fuel injection system (Maji *et al.*, 2014).

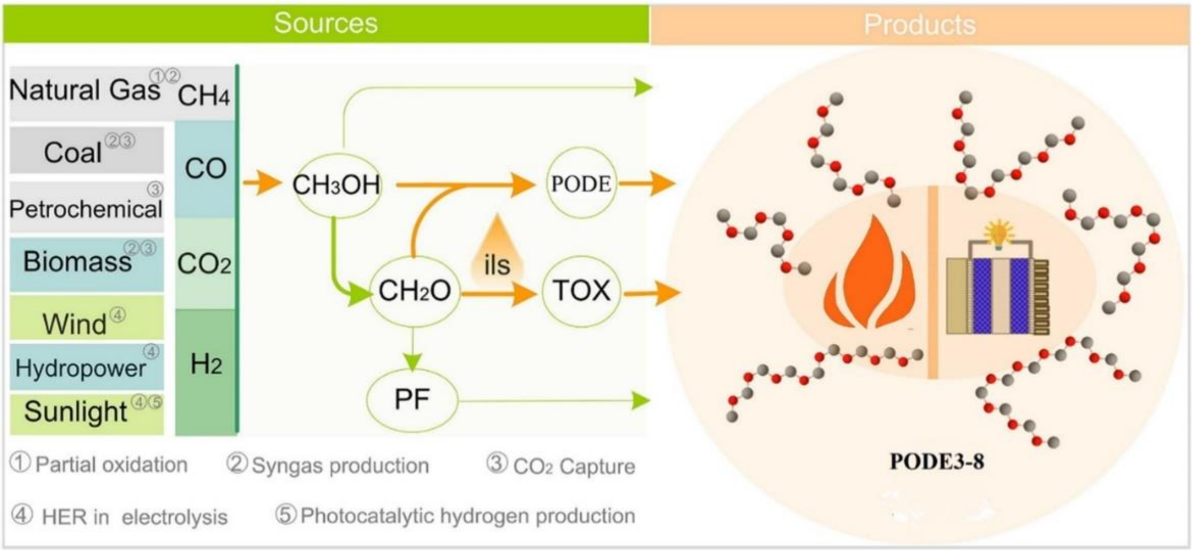

Fig. 3 Pathways of PODE production (Awad *et al.*, 2020)

Table 1.
Physico-chemical and combustion properties ether additives

Additive	Molecular formula	Density (kg/m^3)	Viscosity (cSt)	Latent heat (kJ/kg)	Boiling point (°C)	Cetane number	Oxygen content (%)	Lower heating value (MJ/kg)	Auto-ignition temperature (°C)	Ref.
DEE	$C_4H_{10}O$	710	1.21	356	34.6	125	21	33.9	160	(Sezer, 2011)
DME	CH_3OCH_3	667	-	-	-25	61	35	27	239	(Zhao *et al.*, 2014)
DNBE	$C_8H_{18}O$	770	-	345	144	100	-	32	-	(Kerschgens *et al.*, 2016)
EEA	$C_6H_{12}O_3$	975	1.32	-	156	61	17	-	379	(Sudeshkumar *et al.*, 2012)
EGM	$C_4H_8O_3$	1009.2	1.8	-	187	0.1	46	25.9	-	(Lin and Huang, 2003)
ETBE	$C_6H_{14}O$	742	0.48	-	70	-	16	36	-	(de Menezes *et al.*, 2006)
EXEE	$C_8H_{18}O_3$	910	-	-	189	126	30	-	174	(Kumar *et al.*, 2018)
MXEE	$C_6H_{14}O_3$	950	1.08	-	162	124	36	-	190	(Ommi *et al.*, 2009)
MEA	$C_5H_{10}O_3$	1010	1.10	-	143	-	41	21	392	(Yanfeng *et al.*, 2007)
TAEE	$C_7H_{16}O$	767	0.41	-	102	-	14	-	-	(Aydin *et al.*, 2020)
PODE$_{(1-6)}$	$C_2H_6O(CH_2O)_n$	860-1130	0.36-2.36	-	42-280	74-128	42-49	17.5-22.4	-	(Awad *et al.*, 2020)

However, the lower calorific value is lower than that of conventional diesel fuel, which increases the specific fuel consumption of the engine using the fuel blended with ether additives (Bragadeshwaran *et al.*, 2018)(Nižetić *et al.*, 2021a). In addition, the inherent disadvantage of oxygenated additives, their kinematic viscosity is too low, which seriously affects the lubricating ability of the fuel (Lautenschütz *et al.*, 2016)(Le and Hoang, 2017). As a result, the corrosion rate in the injector and piston ring increases significantly, adversely affecting engine durability. In a study by Rakopoulos et al. (Rakopoulos *et al.*, 2013), the use of additives such as DEE and ethanol in diesel fuel reduced the kinematic viscosity of the blended fuel, increasing the wear of the fuel pump and injector. Another emerging ether additive for biofuels is DBE, which is produced from biomass. It has low viscosity and density, which when mixed with biodiesel improves the characteristic properties of biofuel, leading to improved injection parameters. In the study by Fu et. al (Fu *et al.*, 2019), adding 15% vol. and 30%vol. of DBE into biofuels with DBE15 and DBE30 respectively, result in reduced penetration, also increased spray cone angle and maximum spray width. In another study from Tang et al. (Tang *et al.*, 2017), the experimental results were also similar, with 30% DBE blended with 70% biodiesel, the viscosity and density of the blended fuel decreased, increasing the angle it sprays and the spray area (Hoang, 2019).

Studies using oxygen-rich ether additives to blend with the pyrolysis waste plastic oil (WPO) have attracted much attention from researchers. A recent study by Gnanamoorthi and Murugan (Gnanamoorthi and Murugan, 2019) showed that DEE and MEA were added to WPO to improve the properties of the modified blends and combustion characteristics. MEA additives include both ethers and esters, with high oxygen content to enhance combustion in the cylinder. Moreover, its boiling point and flash point are similar to diesel fuel, for which DEE has a much lower value (Minh and Anh, 2018). While the outstanding advantage of DEE is its very high cetane number and lower viscosity compared to diesel. Therefore, incorporating the addition of DEE and MEA into WPO could have resulted in a more stable, homogenous blend fuel and with physicochemical properties suitable for fuels fed to CI engines without any adjustments.

The influences of ethers such as ETBE and TAEE on density, volatility, viscosity, characteristics at cold temperatures, the cetane number of diesel fuel were investigated in the study of Menezes et al. (de Menezes *et al.*, 2006). The study obtained that the operation of TAEE and ETBE is similar to co-solvents of ethanol in diesel. Furthermore, the evaluation of physicochemical properties obtained reasonable results and the efficiency of the engine is improved significantly in tests with 5% v/v of TAEE concentration (Aydin *et al.*, 2020). However, the flashpoint and distillation curve which represent volatility characteristics are changed and the cetane number decline due to ETBE.

Finally, the auto-ignition temperature of ether additives is lower than that of diesel fuel, which can increase flammability in storage and use. Therefore, many factors should be considered in the selection of suitable ether additives to improve the physicochemical properties of experimental or commercial fuels. In this, factors such as safety potential and cost should be considered in addition to the properties shown from standard measurement methods.

4. Impact of ether additives on engine performance and emission characteristics

4.1 Engine performances

The physicochemical properties of the ether additive have a significant impact on the characteristics of modified fuels as well as the combustion behaviours and engine performances. For instance, studies of Mohan et al. (Mohan *et al.*, 2017) and Jawre et al. (Jawre *et al.*, 2016) have revealed that the increased ignition delay caused by the addition of DEE to diesel fuel reduced the injection time of the blended fuel. Furthermore, the latent heat of blends with DEE is higher. Thus, it was necessary to prolong the fuel injection time to ensure the release the same of energy. However, More et al. (More *et al.*, 2020) has confirmed that a high cetane number is the main cause of an increased ignition delay. A study by Ibrahim (Ibrahim, 2016), the blend of DEE and neat diesel has improved engine performance under all load conditions. With up to 15% DEE participation in the test fuel, the maximum brake thermal efficiency increased by 7.2% while the lowest specific fuel consumption decreased by 6.7%. Kumar et. al (Kumar *et al.*, 2020) performed a test on a VCR (variable compression ratio) diesel engine using mixed fuel D–NM2.5–DEE7.5 (with 7.5%DEE and 90% diesel). Modified blends with BTE rose by 17.4% while BSFC fell by 19.5%. The results revealed the role of DEE in improving the engine characteristics and combustion behavior of the blends compared to pure diesel fuel.

An investigation on CRDI engines by Gnanamoorthi and Murugan (Gnanamoorthi and Murugan, 2019), using diesel fuels, pyrolysis waste plastic oil (WPO) and their mixtures with DEE and MEA have evaluated the role of additives to the ability to improve combustion and engine performance. Indeed, the brake thermal efficiency (BTE) for D50W40DEE10 and D50W50 has been 3.6% and 4.8% lower compared to pure diesel, while BTE for D50W40MEA10 has increased by 5.2% compared to pure diesel, shown in Figure 4a. Furthermore, the exhaust gas temperature (EGT) of WPO is the highest, because the incomplete combustion of WPO fuel takes longer and can burn on the discharge process. EGT for D50W50 increased by 11.2% compared to diesel. More interestingly, WPO was mixed with DEE and MEA, the role of high oxygen content improved complete combustion. EGT for D50W40DEE10 and D50W40MEA10 have seen a decrease of 10.1% and 10.9% compared to WPO respectively, depicted in Figure 4b.

More et al. (More *et al.*, 2020) investigated the diesel engine characteristics for different volume percentages of diethyl ether (DEE) adding into cooking oil (RUCO) biodiesel and diesel blends. In this work, several pilot experimentations commenced to be performed with diesel and blended B20 before adding 0.8%, 1.6%, 2.4%, 3.2%, and 4% of DEE into biodiesel/diesel. This work abided by the IS standards for the estimation of the various properties of biodiesel blends. Investigated results remarked that the density, viscosity, calorific value, and flash point have a dropdown trend due to the concentration of DEE increased which also ascended cetane number. Examination of all fuel samples was conducted on a water-cooled diesel engine at six load modes and a fixed speed. The examination obtained that as contrasting with diesel fuel, the rise of the BTE was up to 16.06% while the reductant of BSFC (Brake specific fuel consumption) was up to 4.12% for the blend of 0.8% concentration of DEE. Double blends of DEE-diesel fuel (D95DEE5 and D90DEE10) and four blends of DEE-ethanol-diesel fuel (D90DEE5E5, D85DEE5E10, D85DEE10E5, and D80DEE10E10) was investigated in the experiment of Paul et al. (Paul *et al.*, 2015). The engine used in this study is a 4-stroke diesel engine, single-cylinder. D95DEE5 (5% of DEE and 95% of diesel fuel) showed an increment of the BTE of the engine. In contrast, D90DEE10 (10% concentration of DEE in Diesel) reduced the BTE of the engine. Although brake-specific energy consumption (BSEC) witnessed a declining trend with D95DEE5, adding more DEE concentration visibly climbed the BSEC of the engine.

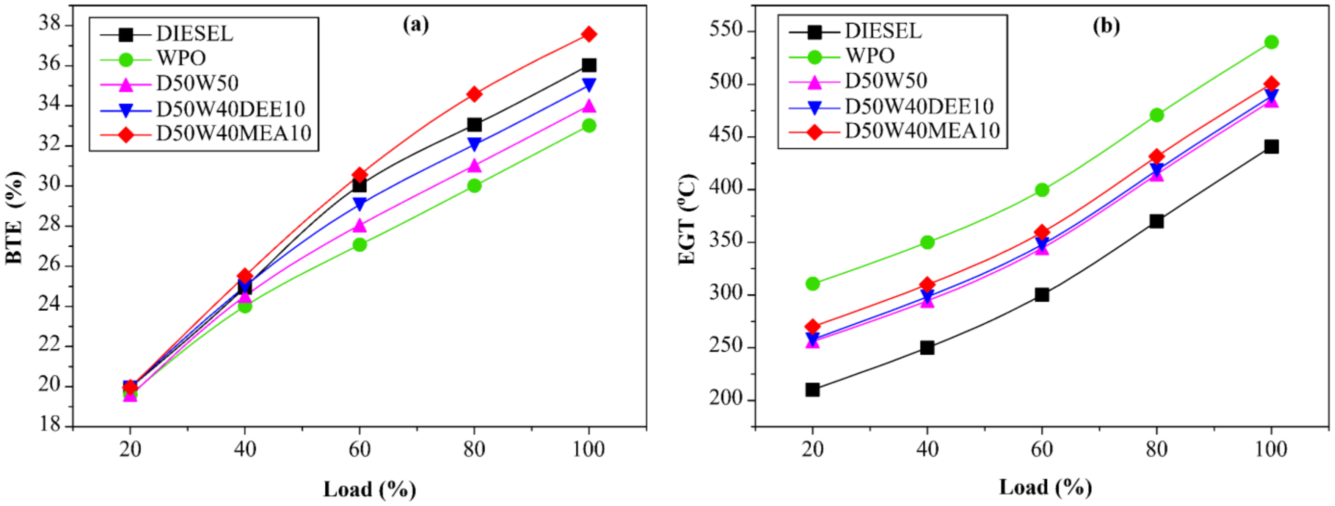

Fig. 4 Change of BTE (a) and EGT (b) for various blends at different loads (Gnanamoorthi and Murugan, 2019)

D80DEE10E10 blend (10% DEE and 10% ethanol with diesel) got the best performance among DEE-diesel fuel mixed with ethanol, which improved the BTE by15.94% and decreased BSEC by 14.26% compared to pure Diesel fuel at the same load equivalent of 1.8 kW. In most of the research studies, the advantage of ether additives was to assist in optimizing the performance and minimizing the emissions due to better physicochemical properties such as cetane number and ignition quality. In addition, a study by Murat et al. (Yesilyurt and Aydin, 2020) on the addition of DEE to B20 biodiesel blends at 2.5%, 5%, 7.5% and 10%vol. fueled for a 4-stroke, single-cylinder, direct injection diesel engine at variable loads and fixed speed. In terms of engine performance, brake thermal efficiency has been reduced by 17.4% while specific fuel consumption has increased by approximately 30% at the maximum DEE addition. The lower calorific value of DEE affects the power generated when a certain amount of fuel is burned. This explains the increase in BSFC when the presence of DEE is more in the secondary and tertiary fuels, and in agreement with similar studies by Das et al.(Das *et al.*, 2018), as shown in Figure 5a. Furthermore, the low cetane number of DEE is the main cause of the shortening of the ignition delay, which has resulted in poor mixing of the fuel-air mixture. As a result, brake specific energy consumption (BSEC) recorded an increase in all secondary and tertiary fuels compared to pure diesel or pure biodiesel. Figure 5b depicts this trend for BSEC. A survey to evaluate the effect of DEE on BSEC was carried out by Rakopoulos et al. (Rakopoulos *et al.*, 2012) also agree on the decrease in energy density of the modified fuels.

More interestingly, the reaction of isobutene and isoamylenes with ethanol results in the formation of Ethers additives which are semi-renewable products (de Menezes *et al.*, 2006). It is not difficult to burn ether additives which particularly include Ter-amyl ethyl ether (TAEE), ethyl ter-butyl ether (ETBE), 2-ethoxy ethyl ether (EXEE), 2-methoxy ethyl ether (MXEE), dimethyl ether (DME), diethyl ether (DEE), di-n- butyl ether (DNBE), etc. A study by Murat et al. (Yesilyurt and Aydin, 2020) aimed to examine experimentally engine characteristics with a variety of diethyl ether (DEE) fractions which play an oxygenated fuel additive role in cottonseed oil biodiesel-diesel fuel blends. The initial step was to carry out several tests with diesel and blended B20. After that, the ternary blends were prepared by mixing 2.5%, 5%, 7.5%, and 10% of DEE by volume into biodiesel-diesel fuel. A single-cylinder, four-stroke, and direct-injection diesel engine were used to test whole the fuel samples under conditions of various engine loads and fixed engine speed. The obtained results from the experiment revealed that compared to diesel fuel, BTE was dropped by 17.39% whereas BSFC was raised by 29.15% with blending 10% of DEE. Besides, in order to improve the use of waste cooking oil (WCO) for DICI engines, Chaudhary et al. (Chaudhary and Gakkhar, 2020) tested the addition of DEE additive to WCO at the ratios of 5%, 10% and 15% on the engine at 100%. of load and steady speed of 1600 rpm. The results recorded an 8.5% improvement in engine performance when WCO fuel was mixed with 15% DEE.

The non-biodegradability of waste plastic is turning it into a terrifying threat to the Earth. The good news is that many man-made methods can treat plastic waste to convert them into value-added products like waste plastic pyrolysis oil. However, it is difficult for pure waste plastic pyrolysis oil to replace diesel because of its lower thermal efficiency because the high viscosity of WPO leads to poorer evaporation and combustion (Noor *et al.*, 2018). Furthermore, using 100% WPO has increased the number of toxic emissions due to its very high aromatic content. Although the WPO tests were blended with pure diesel fuel, performance and emissions characteristics were still not as good as pure diesel fuel (Devaraj *et al.*, 2015). Therefore, the use of additives has been seen as an effective solution to overcome the problems related to the viscosity and density of WPO. In the study by Kaimal et al. (Kaimal and Vijayabalan, 2016), WPO-diesel blends with added DEE additive at the rate of 5%, 10% and 15% by volume were supplied to CI engines to evaluate the dynamic performance. muscle. Brake specific fuel consumption is lower compared to diesel fuel. Moreover, the brake thermal efficiency has also been higher than pure WPO. According to Gnanamoorthi et al. (Gnanamoorthi and Murugan, 2019), in order to improve engine performance and reduce fuel consumption, a survey on CRDI engines was conducted with blended fuels between diesel and waste plastic pyrolysis oil with the addition of oxygen-rich additives include DEE and MEA.

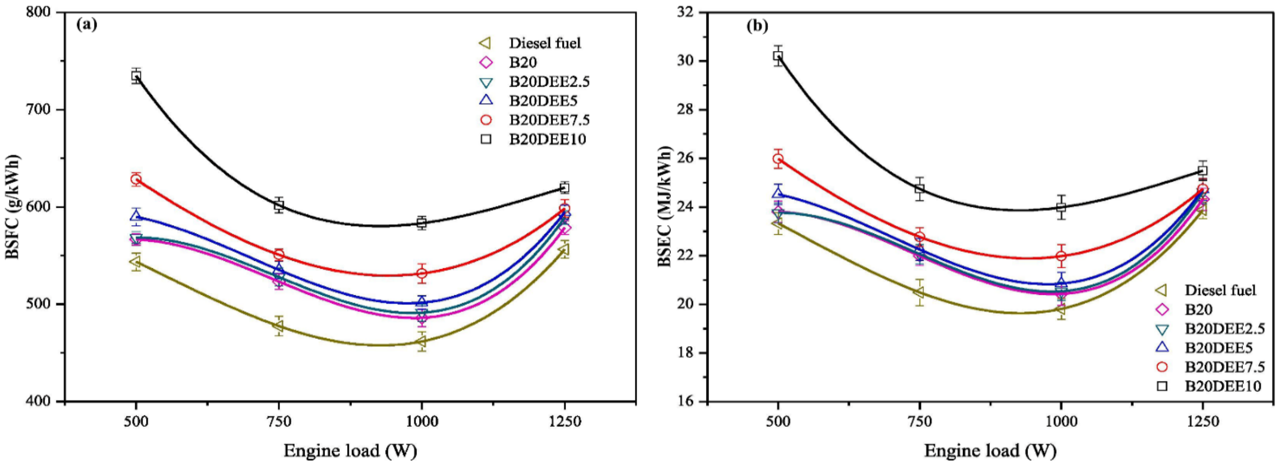

Fig. 5 Change of BSFC (a) and BSEC (b) of modified fuels with DEE at different loads (Yesilyurt and Aydin, 2020)

In terms of brake specific fuel consumption, using pure WPO recorded the highest value, while when BSFC was gradually reduced in the order of D50W50, D50W40DEE10 and D50W40MEA10, but higher in comparison with pure diesel. In general, the exhaust gas temperature of WPO was the highest due to lower volatility and higher viscosity resulting in incomplete combustion. Despite the addition of oxygen-rich additives, the exhaust temperature of D50W40MEA10 was 12.2% higher than that of pure diesel. On the other hand, the exhaust temperature of D50W40MEA10 was recorded 11.4% higher than that of D50W40DEE10 because the oxygen content in MEA was higher than that of DEE.

Several recent studies have confirmed that besides the advantages of alcohol and ether additives, P-series glycol ether additives are emerging as potential organic additive candidates. The most prominent is the 2-Ethoxy Ethyl Acetate (EEA) additive, which can be blended into diesel fuel to improve engine performance and reduce environmental pollution. Sood et al. (Sood *et al.*, 2014) performed tests on 4-stroke, single-cylinder CI engines using D0, D95EED5, D90EED10 and D85EED15 fuels (EED is blended with diesel (D0) in 5%, 10% and 15% by volume). The results revealed the ability to increase brake power and brake thermal efficiency as using the D90EEA10, at full load, the brake power increased by 7.6%, the brake thermal efficiency increased by 7.2% compared to diesel fuel. Furthermore, the solution of adding additives to traditional fuels brings many benefits and advantages to engine characteristics. Indeed, a study by Rao et al. (Rao *et al.*, 2020) reported the positive effects of EEA and NM additives in blended fuels such as D-EEA10-NM2, D-EEA15-NM2, D-EEA20-NM2 and diesel to BTE and BSFC of CI engines running under variable load conditions. In comparison with test fuels, two fuels blended 10%EEA and 15%EEA along with 2%NM were more prominent. BTE increased 1.78% and 0.94% respectively using D-EEA10-NM2 and D-EEA15-NM2, however, BSFC increased approximately 10% and 13% for those 2 test fuels at full load (Nižetić *et al.*, 2021b).

An effort of Sukjit et al. (Sukjit *et al.*, 2012) improved the stability and lubricity of fuel blends and characteristics of combustion by employing methyl ester as a tertiary additive in alcohol (ethanol and butanol)-diesel blends in CI engine. As shown by the results in their work, 15% of all methyl esters in blend could avoid phase separation of fuel blends and retained wear scar diameter of the alcohol-diesel blends following the requirement of the lubricity standard (Labeckas *et al.*, 2018). They concluded that the short carbon chain length and saturated methyl esters are suggested for the improvement of alcohol-diesel blends. Ethylene glycol mono acetate (EGM) is considered as a possible approach to reduce harmful emissions from marine diesel engines (Xuan *et al.*, 2021). EGM has an atomic mass of 104, made up of the elements C, H and O accounting for 46% by weight. The addition of EGM additive to diesel fuel can enhance the oxidation reactions during combustion, resulting in less particulate and toxic gas emission products. In the study of Lin et al. (Lin and Huang, 2003), a 4-stroke, 4-cylinder, the direct-injection marine diesel engine was supplied D100, D95EGM5 and D90EGM10 to evaluate engine performance such as BSFC and EGT. With variable speed and fixed torque, BSFC has increased in the proportion of EGM addition, mainly because EGM has a lower calorific value compared to diesel, while EGT recorded the opposite trend.

The combination of different organic additives to blend with diesel fuel is considered as a solution that takes advantage of the advantages of each type of additive. In a study by Wang et al. (Yanxia and Yongqi, 2007), dimethyl carbonate (DMC) an additive containing 53.3% oxygen was mixed with diesel fuel with the addition of EGM additive, blend fuels included DMC15, DMCEGM5, DMCEGM10, DMCEGM15 AND DMCEGM20. In terms of engine performance, power was reduced with the increase of DMC and EGM additions, because the energy density of the 2 additives was lower than that of diesel. In comparison with diesel fuel, maximum power reductions were recorded of 2%, 4%, 6% and 8% for DMCEGM5, DMCEGM10, DMCEGM15 and DMCEGM20 respectively. DME is a potential renewable fuel with a very high cetane number, so it can be used in blending with secondary and tertiary fuel blends to improve the cetane number of biodiesel (Wang and Yao, 2020). In a study by Joy et al. (Joy *et al.*, 2019), two fuel samples formed from cashew nut shell oil biodiesel with 10% and 20% DME were tested on a 4-stroke 1-cylinder diesel engine to investigate engine characteristics. The results revealed that the BTE and BSFC of CBD80DME20 and CBD90DME10 were both increased compared to diesel and CBD100. Indeed, in a comparison of CBD80DME20 and biodiesel, BTE increased by 1.6% and BSFC decreased by 4.1%, Figure 6 shows that change. Table 2 shows the significant effects of ether additives on engine performance such as BTE, BSFC and ETG.

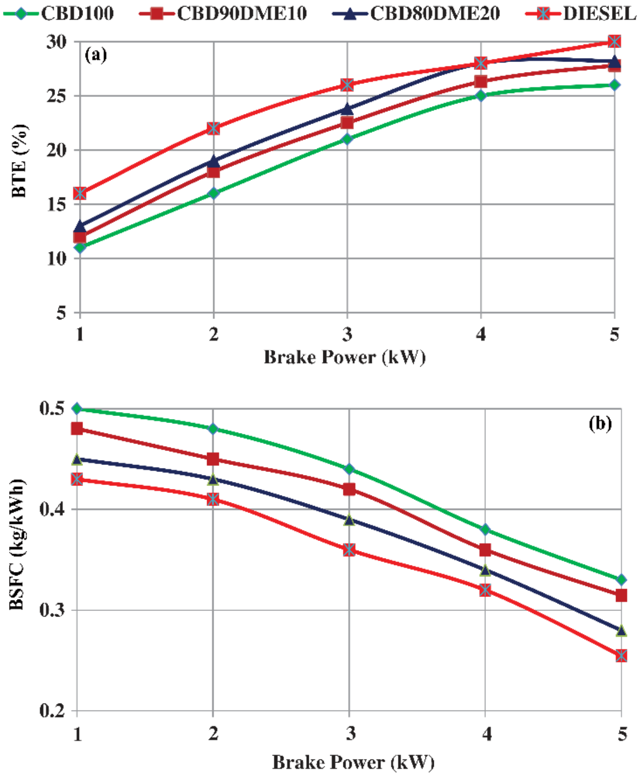

Fig. 6 The differences in BTE (a) and BSFC (b) of blends with DME at various brake power (Joy *et al.*, 2019)

Table 2
Summary of the overall performance in diesel engine using ether additives

Additive	Concentration	Test Condition	BTE	BSFC	EGT	References
DEE	5% DEE	Different loads (20, 40, 60, 80 and 100%)	↑ compared to diesel fuel and other blends	-	↑ compared to diesel fuel and other blends	(Mohanan *et al.*, 2003)
	10% DEE	Injection timing at 27° BTDC	↓ compared to diesel fuel	-	Close to diesel fuel	
	15% DEE	Engine speed at 1500 rpm	↓ compared to diesel fuel and 10% DEE	-	Close to diesel fuel	
	20% DEE		↑ compared to diesel fuel at loads of 60 to 100% but ↓ at other loads	-	↓ compared to diesel fuel	
	25% DEE		↑ compared to diesel fuel at loads of 60 to 100%, but ↓ at	-	↓ compared to diesel fuel	
DEE	B4 (4%)	Different loads (25, 50, 75 and 100%)	Not change much compared to diesel fuel	-	↑ compared to diesel fuel but lower than B5	(Kapilan *et al.*, 2008)
	B5 (5%)		↑ compared to diesel fuel and other blends	-	↑ compared to diesel fuel and other blends	
	B6 (6%)		↑ compared to diesel fuel	-	↑ compared to diesel fuel but lower than B5	
	B7 (7%)		↑ compared to diesel fuel at 25 and 50% load, ↓ at 75 and 100% load.	-	Not change much compared to diesel fuel	
DME	14% vol.	Different EGR rates (9, 18 and 27%)	↑ compared to diesel fuel	↓ compared to diesel fuel	-	(Zhao *et al.*, 2014)
	30%vol.	Different BMEP (0.25 and 0.5 MPa)	↑ compared to diesel fuel and 14%.	↓ compared to diesel fuel and 14%.	-	
DEE	DE2D	Different BMEP (0.1, 0.2, 0.3, 0.4 and 0.45 MPa)	↑ compared to diesel fuel but ↓ significantly at BMEP of 0.45 MPa	close to diesel fuel	↑ compared to diesel fuel but only ↓ at 0.3-0.45 MPa of BMEP	(Patil and Thipse, 2015)
	DE5D		Not change	↑ compared to diesel fuel	↑ compared to diesel fuel but only lower at 0.45 MPa of BMEP	
	DE8D		↑ compared to diesel fuel	close to diesel fuel	↓ compared to diesel fuel but ↑ compared to DE15D	
	DE10D		close to diesel fuel	↑ compared to diesel fuel	↓ compared to diesel fuel↑ compared to DE15D	
	DE15D		↑ compared to diesel fuel and other DEE-diesel	↓ compared to diesel fuel and other DEE-diesel.	↓ compared to diesel fuel and other DEE-diesel.	
	DE20D		close to diesel fuel	↑ compared to diesel fuel	↓ compared to diesel fuel ↑ compared to DE15D.	
DME	Equivalence ratio from 0.4 to 0.7	Different crank angles (-50° to 50°)	-	↑ by 100 g/kWh compared to diesel fuel	-	(Kim and Park, 2016)
DEE	10% vol.	Different BMEP (0.2, 0.3, 0.4, 0.5, 0.6, 0.7 and 0.8 MPa)	-	↑ compared to diesel fuel.	-	(Lee and Kim, 2017)
EEA	5EEA	Different loads (0, 20, 40, 60, 80 and 100%)	↑ compared to diesel fuel	↑ compared to diesel fuel	-	(Deepanraj *et al.*, 2011)

4.2. Emission characteristics

According to Yesilyurt et al. (Yesilyurt and Aydin, 2020), it is also found that the average HC, smoke, and NO_X emissions exhausted by the engine fueled with ternary blends were 12.89%, 4.12%, and 8.84%, respectively lower than those of diesel fuel. The trend of CO emission exhibited an increase with the diesel fuel at higher DEE concentration through lower concentration at the maximum load recorded a slump up to 40.09% of CO emission. Incidentally, the CO_2 also declined at high loads conditions. However, the combustion behaviours vaguely deteriorated when the CI engine run on all ternary blends. As a result, DEE can be considered as a favourable option for removing the major trouble in using cottonseed oil biodiesel. Further remarkable highlight demonstrated that the 10% (by vol.) of DEE in to blend is probably a potential technique for utilizing biodiesel/diesel blend efficiently in the CI engines without modifying. Additionally, in the study of More et al. (More *et al.*, 2020), all tested fuels have an analogous trend at whole loading conditions and ratios of compression. According to the obtained results, the emissions of CO, HC, and NOx formatted by burning biodiesel-DEE-diesel blends in CI engine had the highest drop by 20.41%, 34.69%, and 23.33% in comparison with diesel fuel at remarkable working conditions. Lower carbon content in the ternary blends caused the downward trend of CO_2 emission. A notable comparison with diesel fuel showed 15.07%, 3.45%, and 14.70 % minimization of CO, HC, and NOx emissions respectively, are provided by 0.8% concentration of DEE at CR15 in the ternary blend. More remarkably, in minimum content of DEE, luminous results are obtained by the A0.8B19.2 blend in characteristics of both performance and emission at CR15. Furthermore, Tree et al. (Tree and Cooley, 2001) compared the emissions (NOx and PM) consequent in the combustion of DEE with that of diesel fuel in the diesel engine. They explored that DEE creates less PM for a given level of NOx. A similar decline in the emissions of NOx and smoke by employing DEE-diesel blend fuel from a DI diesel engine with EGR was gained in the research of Anand et al. (Anand and Mahalakshmi, 2007) which was up to 15%. A diesel engine equipped with EGR and fueled DEE-diesel blend was depicted as a feasible method for dropping the PM and NOx trade-off.

According to Paul et al. (Paul *et al.*, 2015), the application of DEE in diesel fuel reduced the exhausted gases such as PM, CO, HC, and NOx (with 10% DEE), nevertheless, 5% concentration of DEE (D95DEE5) shows a different trend in NOx emission. Emissions have significant fall (Figure 7), PM by 91%, CO by 53%, D80DEE10E10 in comparison to diesel. On the other hand, tests using DNBE additives added to diesel fuel to feed a 4-stroke, single-cylinder CI engine has yielded positive information on HC, CO and PM emissions. At the same time, with the condition of increasing load, the improvement in emission characteristics is more obvious for DNBE additive blend fuel (Kerschgens *et al.*, 2016). In a study on the emission characteristics of diesel engines using B20 biodiesel fuel with the addition of DEE additives up to 10%, Yesilyurt et al. (Yesilyurt and Aydin, 2020) confirmed that NOx, smoke and HC emissions reduced by 8.8%, 4.1% and 12.9%, respectively, compared to pure diesel fuel. Moreover, with the addition of 5%DEE to B20 fuel, CO emissions are reduced by almost half compared to when using diesel fuel at the same test condition. Pochareddy et al. (Pochareddy *et al.*, 2017) studied the emission characteristics of CI engines using fuel mixed by sapote seed oil methyl ester, 5%DEE and diesel. It can be found that CO, smoke and HC emissions are significantly reduced compared to pure diesel fuel, while exhaust gas temperature and NOx emissions increase. In a study by Chaudhary et al. (Chaudhary and Gakkhar, 2020), a direct injection diesel engine was operated at 1600 rpm and full load, supplying waste cooking oil (WCO) blended with 5%, 10% and 15% vol. of DEE in 55% vol. of diesel, to evaluate the possibility of improving emission characteristics. The results and discussion of NOx emissions revealed that adding up to 15% DEE reduced NOx concentrations by about 4.5 times compared with WCO45 fuel (45% WCO and 55% diesel)(Balasubramanian *et al.*, 2021c).

Geng et al. (Geng *et al.*, 2017) experimented studied using DME-diesel fuel as a renewable alternative fuel for CI engines. The measured results proposed a longer injected delay timing, reductant in peak pressure in the cylinder, and shorter delay ignition which was different to those offered by using blended alcohol in diesel fuel. Moreover, PM tended to fall substantially with the growth of DME content. Moreover, Işık et. al (Işık *et al.*, 2020) researched generator diesel engines using blended fuels of diesel, biodiesel and DME additives such as B10DME10, B25DME25, B25, B100 and D2 (ULSD diesel) to evaluate combustion and emission characteristics (Tran *et al.*, 2019). The addition of DME to biofuels has improved the viscosity of the blended fuel, resulting in improved combustion quality in the cylinders. In terms of emission characteristics, the addition of DME resulted in significant reductions in CO and HC emissions compared with B100 and D2 fuels at the loading modes, while NOx emissions increased slightly (Tran *et al.*, 2021).

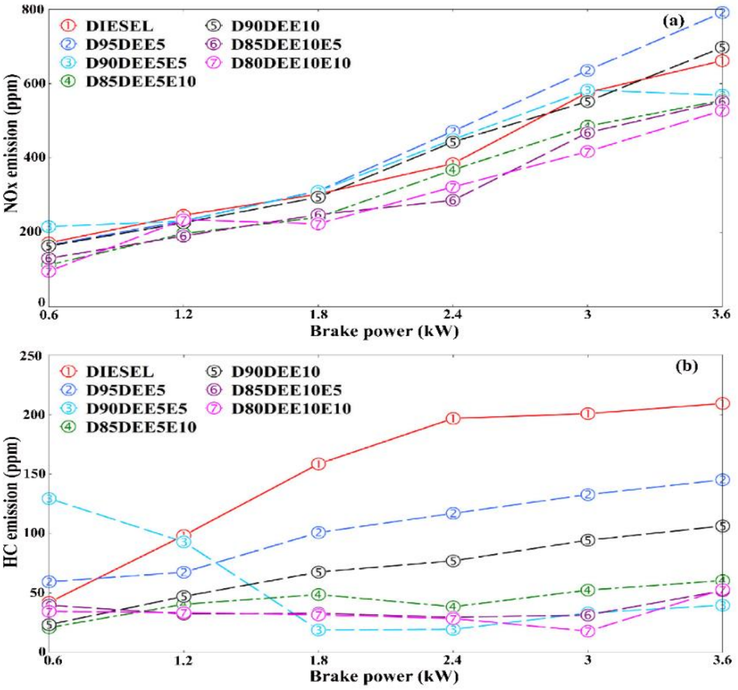

Fig. 6 The change of NOx and HC emission for modified blends with DEE (Paul *et al.*, 2015)

Adhinarayanan et al. (Adhinarayanan *et al.*, 2020) analyzed the effects of using blended fuels such as D70L20D10 and D70L20DNBE10, which were produced by replacing 10% by vol. of LDPE oil in D70L30 blend fuel with 1-decanol and di-n-butyl ether, on the combustion and emission characteristics of 4-stroke, single-cylinder CI engines. The addition of DNBE improved brake thermal efficiency by 0.7% and 3.1% compared to diesel and D70L30 respectively (Figure 8). More interestingly, NOx emissions were found using the D70L20DNBE10 to be reduced by 5.7% compared to the D70L30. Smoke opacity is lower than D70L30 but higher than diesel fuel. The study of Miyamoto et al. (Miyamoto et al., 2000) concluded that the THC, NOx and CO emissions from CI engines decreased significantly with an increasing amount of DBE addition to conventional fuel and biodiesel. The above results can be derived from the abundant oxygen content of the DBE as well as the reduction of the Sauter Mean Diameter of the blended fuel to improve the injection characteristics of the biofuel (Guan *et al.*, 2015).

In terms of 2 ethoxy-ethyl-acetate additives, the study of Wei et al. (Wei *et al.*, 2017) on emission characteristics of direct injection, 4-stroke and single-cylinder diesel engines using diesel and EEA blend fuels including 5EEA, 10EEA and 15EEA, the role of EEA additive has been demonstrated. Research results have revealed that increasing the additive EEA in the fuel blend can reduce the concentration of pollutant emissions such as HC and CO. The reason given by the author is due to the increase of atomic oxygen content from the EEA leading to more complete combustion. A study on the impact of EEA on emission characteristics by Sood et al. (Sood *et al.*, 2014) showed that when the added EEA content was increased from 5% to 15%, the smoke opacity decreased by 19%, while the reduction in CO and HC emissions were also recorded 16% and 12% respectively in the loading modes. In testing with a direct injection CI engine with a compression ratio of 17:1 at five different loads and at a steady speed, the emission characteristics were improved with the contribution of EEA and NM additives in diesel fuel (Rao *et al.*, 2020). Specifically, with D-EEA10-NM2, HC and smoke emissions recorded a decrease of about 48.3% and 62.3% respectively, while there is an increase of about 54.3% and 23.8% for NOx and CO emissions respectively in comparison with diesel fuel (Dung and Anh, 2020). Furthermore, NOx and CO emissions have also been reported to increase 55.2% and 14.7% respectively for D-EEA15-NM2 blended fuel compared to conventional fuel, while the improvement in HC and smoke emissions is said to be reduced by about 59% and 60% respectively.

According to Gnanamoorthi et al. (Gnanamoorthi and Murugan, 2019), the emission characteristics of a single-cylinder, 4-stroke CRDI diesel engine was revealed in a study using diesel-WPO blended fuels with the addition of DEE and MEA additives. Regarding CO emissions, the atomic oxygen content in the fuel reduced the emission concentrations in all WPO blend fuels. In comparison with pure diesel fuel, CO emissions of 50D40W10DEE, WPO and 50D40W10MEA decreased by 15.8%, 20.3% and 22.4% respectively. In addition, unburnt hydrocarbon (UHC) emissions have generally tended to increase when the fuel contains many aromatic compounds that are difficult to decompose by heat. As a result, the UHC content in the exhaust emission from engines using WPO was 23% higher in comparison with pure diesel fuel. More interestingly, when adding oxygen-rich additives to the WPO-diesel blend fuel, UHC emissions were reduced, specifically, the UHC of 50D40W10DEE and 50D40W10MEA was 5.7% and 11.3% lower, respectively, than that of pure diesel fuel. Thus, the excess of atomic oxygen by the addition of DEE and MEA additives completely oxidized the remaining unsaturated hydrocarbons of WPO for cleaner combustion. In terms of NOx emissions, the presence of oxygen in WPO and its higher viscosity and density resulted in NOx emissions being about 23% higher than pure diesel fuel (Al-Tawaha *et al.*, 2018). Even better, in comparison with pure diesel fuel, the DEE additive with higher oxygen concentration, higher cetane number and higher heat of vaporization promoted faster and shorter combustion. That has helped the NOx emission of D50W40DEE10 be recorded to be 5.3 % lower in comparison with pure traditional fuel. However, the higher density MEA additive led to a slight increase in NOx emissions compared with pure diesel fuel. Moreover, it is observed that the smoke opacity of WPO and D50W50 fuel is higher than that of diesel fuel (Thu and Anh, 2017). However, the addition of DEE and MEA additives stimulated complete combustion, resulting in a 7.1% and 15.5% reduction in smoke opacity of D50W40DEE10 and D50W40MEA10 respectively compared with diesel.

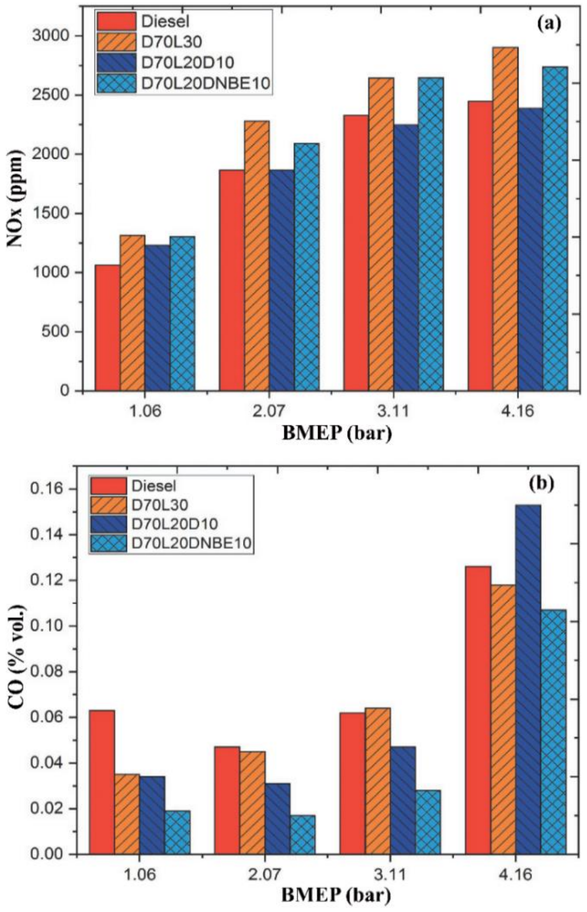

Fig. 8 The change of NOx (a) and CO (b) emission for blends with di-n-butyl ether (Adhinarayanan et al., 2020)

In the marine field, diesel engines dominate almost completely because of their ability to provide a large capacity that is difficult to find a replacement engine. However, the emission problems from diesel engines with the environment are very worrisome. To reduce particulate, smoke and NOx emissions, the use of organic additives such as EGM to improve combustion quality and reduce environmental pollution has attracted many scholars (Chan, 2018). A study by Lin and co-workers (Lin and Huang, 2003) on 4-cylinder marine diesel engines with different rates of EGM addition to conventional fuels investigated the output parameters of NOx, CO_2 and CO. The variable rate regime test data revealed that when the EGM addition rate was increased from 0% to 10%, both CO_2 and CO emissions decreased, while NOx emissions increased with the speed range below 1200 rpm, but turned to decrease at a higher speed range (Shoar *et al.*, 2021).

A study by Yanxia et al. (Yanxia and Yongqi, 2007) was performed on a 4JB1 diesel engine using diesel fuel and the fuels were mixed with DMC and EGM to improve emission parameters from the engine. Indeed, at full load, using DMCEGM15 resulted in a maximum smoke emission reduction of approximately 59% compared to diesel fuel, however, test data also noted a role in smoke emission reduction of DMC was better than EGM. Regarding NOx emissions, there was little effect of the addition of the DMC-EGM surcharge on NOx emissions. Indeed, at a low load, the use of DMCEGM5 and DMCEGM10 may have slightly reduced NOx emissions in the comparison with pure diesel, but with DMCEGM10 and DMCEGM15 a slight increase of NOx was recorded. Meanwhile, the mixed fuel of DMC, EGM and diesel caused NOx to increase slightly at higher loads. The addition of DMC and EGM additives to diesel fuel have both revealed sharp reductions in CO and HC emissions at higher loads. Thus, this has demonstrated the potential to use diesel fuel blended with DMC and EGM in controlling pollutant emissions (Vinh *et al.*, 2018).

PODE is attracting a lot of interest from researchers about alternative fuels. Current pilot studies have been focusing on the addition of PODE additives to secondary or tertiary fuels to improve combustion quality and performance as well as reduce negative emissions effects due to the high oxygen content, high flash point and cetane number. A comparative evaluation study by Awad et al. (Awad *et al.*, 2020) showed very significant effects of PODE on the emission characteristics of CI engines. The evolutions of changes in HC, CO and NOx emissions are shown in Figure 9. The strongest reduction in CO and HC emissions was reported to be 20% with PODE (number of links 3-4) while that NOx emissions increase when PODE is involved (Wu *et al.*, 2021)(Zhu *et al.*, 2021).

Table 3 presents a summary of the prominent effects of ether additives on the emission characteristics (PM, CO, HC and NOx) of CI engines.

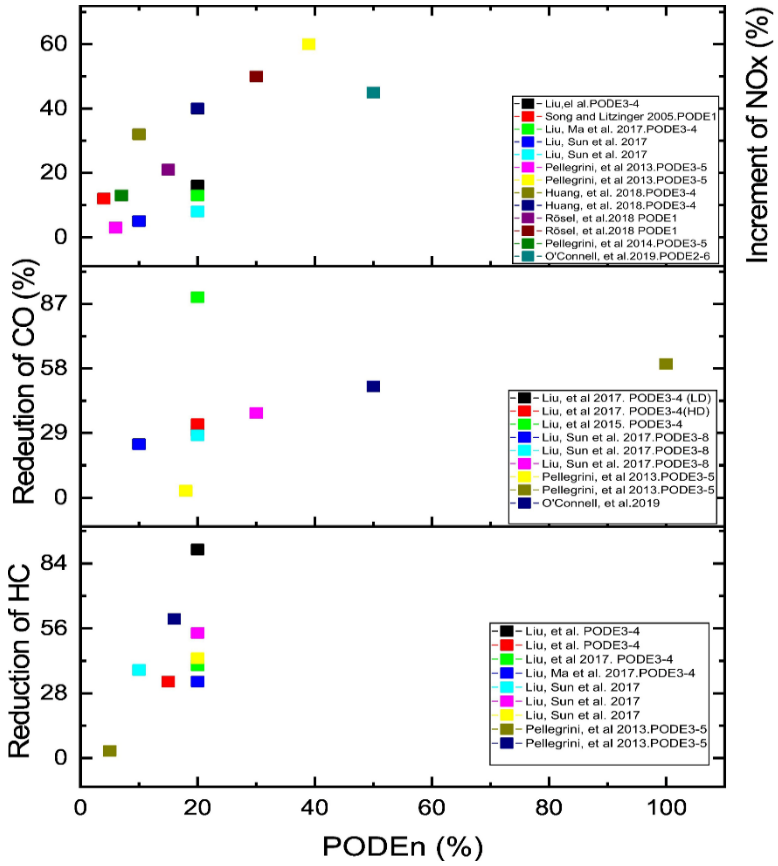

Fig. 9 Evolution of changes in HC, CO and NOx emissions according to the proportion of PODE participation in the adjusted fuel (Awad et al., 2020)

Table 3
Summary of engine emission characteristics using ethers and esters compound additives

Additive	Concentration	Test condition	NO_X	CO	HC	PM/Soot	Ref.
DEE	5% DEE	Different loads (20, 40, 60, 80 and 100%) Injection timing at 27° BTDC Engine speed at 1500 rpm	-	↓ compared to diesel fuel and 10% DEE	-	(smoke) ↓ compared to diesel fuel	(Mohanan *et al.*, 2003)
	10% DEE		-	↓ compared to diesel fuel	-	↑ compared to diesel fuel	
	15% DEE		-	↑ compared to diesel fuel	-	↑ compared to diesel fuel 10% DEE	
	20% DEE		-	↑ compared to diesel fuel and 15% DEE	-	↑ compared to diesel fuel and 15% DEE	
	25% DEE		-	↑ compared to diesel fuel and 20% DEE	-	↑ compared to diesel fuel and 20% DEE	
DEE	B4 (4%)	Different loads (25, 50, 75 and 100%)	↑ compared to diesel fuel but lower than other blends	↓ compared to diesel fuel but higher than other blends	↓ compared to diesel fuel but higher than other blends	↓ compared to diesel fuel but higher than other blends	(Kapilan *et al.*, 2008)
	B5 (5%)		↑ compared to diesel fuel	↓ compared to diesel fuel	↓ compared to diesel fuel	↓ compared to diesel fuel, lower than B4	
	B6 (6%)		↑ compared to diesel fuel	↓ compared to diesel fuel	↓ compared to diesel fuel	↓ compared to diesel fuel, lower than B5	
	B7 (7%)		↑ compared to diesel fuel	↓ compared to diesel fuel	↓ compared to diesel fuel	↓ compared to diesel fuel but lower than other blends	
DME	14% vol.	Different EGR rates (9, 18 and 27%) Different BMEP (0.25 and 0.5 MPa)	↓ compared to diesel fuel	↑ compared to diesel fuel	↑ compared to diesel fuel	(smoke) ↓ compared to diesel fuel	(Zhao *et al.*, 2014)
	30%vol.		↓ compared to diesel fuel and 14% DME	↑ compared to diesel fuel and 14% DME	↑ compared to diesel fuel and 14% DME	(smoke) ↓ compared to diesel fuel and 14% DME	
DEE	DE2D	Different BMEP (0.1, 0.2, 0.3, 0.4 and 0.5 MPa)	↓ compared to diesel fuel but ↑ with BMEP over 0.3 Mpa	No change compared to diesel fuel	↑ compared to diesel fuel, only ↓ with BMEP under 0.1 Mpa	↓ compared to diesel fuel	(Patil and Thipse, 2015)
	DE5D		↓ compared to diesel fuel	↓ compared to diesel fuel	↑ compared to diesel fuel, only ↓ with BMEP under 0.1 Mpa	↓ compared to diesel fuel	
	DE8D		↓ compared to diesel fuel	No change compared to diesel fuel	↑ compared to diesel fuel	↓ compared to diesel fuel	
	DE10D		↓ compared to diesel fuel	↓ compared to diesel fuel but ↑ with BMEP of 0.25 to 0.4 Mpa	↑ compared to diesel fuel	↓ compared to diesel fuel	
	DE15D		↓ compared to diesel fuel	↓ compared to diesel fuel	↑ compared to diesel fuel, only ↓ with BMEP under 0.1 Mpa	↓ compared to diesel fuel	
	DE20D		↓ compared to diesel fuel and lower than other blends	↓ compared to diesel fuel	↑ compared to diesel fuel, only ↓ with BMEP under 0.1 Mpa	↓ compared to diesel fuel but ↑ with BMEP over 0.35 Mpa	
DME	Equivalence ratio from 0.4 to 0.7	Different crank angles (-50° to 50°)	↓ compared to diesel fuel	-	-	↓ compared to diesel fuel	(Kim and Park, 2016)
DEE	DEE10 (10% vol.)	Different BMEP (0.2, 0.3, 0.4, 0.5, 0.6, 0.7 and 0.8 MPa)	↑ compared to diesel fuel	↓ compared to diesel fuel	↓ compared to diesel fuel	↓ compared to diesel fuel	(Lee and Kim, 2017)

EGM	D95EGM5 (5%)	Different speeds (800, 1000, 1200, 1400, 1600, 1800 and 2000 rpm) Different brake torques (2, 4, 6, 8, 10 and 12 kgf-m)	↑ compared to diesel fuel at speed of 800 to 1200 rpm and ↓ at speed of 1400 to 2000 rpm	↓ compared to diesel fuel	-	-	(Lin and Huang, 2003)
	D90EGM10 (10%)		↑ compared to diesel fuel at speed of 800 to 1200 rpm and ↓ speed of 1400 to 2000 rpm	↓ compared to diesel fuel and D95EGM5	-	-	
MEA	DMEA10 (10%)	Different speeds (800, 1000, 1200, 1400, 1600, 1800 and 2000 rpm) Different BMEP (0.2, 0.3, 0.4, 0.5 and 0.6 MPa)	↑ compared to diesel fuel	-	-	-	(Yanfeng *et al.*, 2007)
	DMEA15 (15%)		↑ compared to diesel fuel	↓ 30.8% compared to diesel fuel	↓ 18.2% compared to diesel fuel	(Smoke) ↓ 50% compared to diesel fuel	
	DMEA20 (20%)		↓ compared to diesel fuel	↓ 65.4% compared to diesel fuel	↓ 36.4% compared to diesel fuel	(Smoke) ↓ 60% compared to diesel fuel	
EEA-BE	5EEA	Different brake torques (5, 10, 15, 20, 25 and 30 Nm)	↑ compared to diesel fuel	↓ compared to diesel fuel	↓ compared to diesel fuel	(Smoke) ↓ compared to diesel fuel	(Srinivasan and Devaradjane, 2008)
	10EEA		↑ compared to diesel fuel	↓ compared to diesel fuel	↓ compared to diesel fuel	(Smoke) ↓ compared to diesel fuel	
	15EEA		↑ compared to diesel fuel	↓ compared to diesel fuel	↓ compared to diesel fuel	(Smoke) ↓ compared to diesel fuel	
	15BE		↑ compared to diesel fuel and 15EEA	↓ compared to diesel fuel and 15EEA	↓ compared to diesel fuel and 15EEA	↓ compared to diesel fuel and 15EEA	
EEA	5EEA	Different loads (0, 20, 40, 60, 80 and 100%)	↑ compared to diesel fuel	↓ compared to diesel fuel	↓ compared to diesel fuel	↓ compared to diesel fuel	(Deepanraj *et al.*, 2011)

5. Challenges and future directions

Transparent and long-term strategies for sustainable energy use and management based on renewable energy sources (Balasubramanian *et al.*, 2021b) and integration of Internet of Things technologies (Chau *et al.*, 2021) are seen as the brightest solutions to overcome fossil energy depletion and global environmental pollution. More importantly, the sustainable energy development policies of governments (Xuan and Viet, 2021)(Dong *et al.*, 2021) will be the essential key for research on renewable and sustainable energy to be widely deployed in production and society. Organic additives are emerging with many promising candidates such as alcohol, ether, ester, DMF, etc. The addition of such additives to biodiesel has contributed significantly to improving combustion quality and reducing emissions from CI engines (Devarajan *et al.*, 2019). In particular, recently, furan-based additives have attracted more attention because of their huge production potential from biomass as well as their compatibility with conventional fuels and engines (Ong *et al.*, 2020). In the future, the combination of many different additives to form tertiary and quaternary fuel will promote synergistic effects in improving engine performance and reduce negative environmental impacts (Nayaka *et al.*, 2021)(Gonca and Genc, 2021). In addition, the use of carbon or metal nanoparticle additives (Hoang, 2021)(Murugesan *et al.*, 2021), as well as the development of advanced injection techniques (Hoang, 2020) are also considered an alternative or combined option to overcome the disadvantages of biofuels. However, the economic, environmental and engine durability studies when using organic additives also need to be considered more thoroughly (Anh and Anh, 2019). More importantly, the strategies using electric vehicles (Nguyen *et al.*, 2020), development of novel material for energy storage and energy management (Subramanian *et al.*, 2021) should be considerably focused. In addition, the trends of biofuel production integrated with the circular economy (Atabani *et al.*, 2021), as well as the support of the policy of government in renewable energy (Pandey *et al.*, 2021) should be conducted in order to promote the biofuel production progress as fast as possible, and still meet the critical requirement relating to minimum secondary pollution.

6. Conclusions

Organic or oxygenated additives have been introduced to improve combustion in CI engines. This work specifically addressed ether additives, which are claiming great potential in the goal of sustainable renewable biofuels. Based on recent relevant literature, an integrated assessment of the properties of ether additives added into base fuels was discussed in this study to clarify their role in combustion behaviour and emissions formation.

The results showed that, with higher concentrations of oxygen in the composition of ethers, the added atomic oxygen was richer in the blended fuel, resulting in improved overall combustion efficiency. The presence of fairly high oxygen content in MEA, DME, EXEE, etc. promoted complete combustion, resulting in reduced PM, HC and CO emissions. A rather prominent advantage of using ether additives in biofuels is that the maximum combustion temperature has been reduced and simultaneous combustion leads to a reduction in NOx emissions formed in most of the studies. However, the energy content of ether additives is lower than that of diesel and biodiesel fuels, resulting in lower heat generated when oxidizing the fuel mixture in the combustion chamber. As a result, brake specific fuel consumption may be slightly reduced compared to conventional fuel.

Finally, organic additives are playing a very important role in improving the properties of diesel and biodiesel fuels to improve combustion efficiency and minimize negative impacts on the environment. However, to optimize the outstanding properties of ether additives in studies of their effects on combustion, emission formation and engine characteristics are still limited. Therefore, optimization studies on blending ratio, type of organic additive, operational modes, and type of biofuel need to be expanded in the future.

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