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A review on effects of diethyl ether on cyclic variations in diesel engines

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ABSTRACT

Diethyl ether (DEE) can be used in diesel engines as a fuel or fuel additive. The review study was compiled from the findings of several studies in this area. The diverse techniques are employed to mitigate the detrimental pollutants emitted by diesel engines. The first approach to reducing emissions involves altering the fuel system and engine design to improve combustion, but this is an expensive and time–consuming process. The utilization of various exhaust gas devices, such as a particle filter and catalytic converter, is necessary for the second way. However, the engine performance could be negatively impacted by these tools. Additionally, these exhaust devices increases the vehicle and maintain costs. The use of different alternative fuels or fuel additives is the third way that reduces emissions while improving engine performance. The particulate matter (PM), smoke, and nitrogen oxides (NOx) are the main environmental pollutants released by diesel engines into the atmosphere. The decreasing PM and NOx emissions at the same time is practically very difficult. The majority of researches indicate that using alternative fuels, such as natural gas, biogas, and biodiesel, or blending additives with conventional or alternative fuels, is the best way to reduce emissions. However, the characteristics of the fuel have a significant influence on cycle variations, which have a significant impact on engine performance, fuel economy, and emissions. Therefore, it is very important that the results of studies on the impact of DEE on cyclic variation are evaluated together to practice applications and to guide future studies. As a result, the primary focus of this study is on the usage of DEE as a fuel or fuel additive with different diesel engine fuels. The aim of this review is to investigate, using the available knowledge in literature, how DEE affects cyclic variations.

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1. Introduction

Both automobiles and heavy–duty trucks frequently employ diesel engines [1]. These internal combustion engines exhibit dependability, durability, and great efficiency [2]. Unfortunately, the high emissions of diesel engines cause the problems since they release smoke, sulfur oxides (SOx), nitrogen oxides (NOx), particulate matter (PM), and total gaseous hydrocarbons (THC) [3, 4]. It is thought that switching from commercial fuels to alternative fuels derived from renewable resources will be the most effective strategy to minimize these emissions [5]. However, there are operational and technological constraints when employing renewable alternative fuels, and doing so will require extensive engine structural adjustments in order to replace fossil fuels [6]. The adjustments of engine construction are not necessary to lower emissions because fuel–side modification techniques like blending, emulsification, and oxygenation offer a simple solution. Enhancing fuel volatility, lowering fuel density, cutting fuel sulphur, reducing aromatic content, raising cetane number, and lowering fuel density can all be used to modify diesel fuel to lower exhaust emissions while maintaining engine performance. Diesel fuel containing oxygenates is one example of this [7]. The oxygenated fuels are thought to be the best option among alternative fuels. The emissions of diesel engines can be effectively reduced by using diethylene glycol dimethyl ether (DGM), dimethoxy methane (DMM), dimethyl ether (DME), methyl tertiary butyl ether (MTBE), dibutyl ether (DBE), dimethyl carbonate (DMC), methanol, ethanol, and diethyl ether (DEE) [8–9]. These oxygenated fuels can be utilized in their pure form, mixed with regular diesel fuel, or blended with other alternative fuels like biodiesel [10]. The reducing PM and other hazardous emissions from diesel engines is largely dependent on the oxygen content of the fuel's molecular structure. However, NOx emissions can change based on the engine's operating parameters; they can go up or down in certain situations [11, 12]. Because DEE is both an oxygenated fuel and a cetane improver, it is especially well suited for diesel engines [13]. The purpose of this study is to investigate the use of DEE as a fuel or fuel additive in various diesel engine fuels. The engine's cyclic variations can be greatly altered by the fuel used, and this has a substantial impact on the engine's performance, fuel consumption, and exhaust pollutants. Thus, based on the literature, this review study examines how the addition of DEE affects the cyclic variations.

2. Properties of Diethyl Ether

As seen in Figure 1, diethyl ether (DEE) is the simplest ether expressed by its chemical formula $CH_3CH_2–O–CH_2CH_3$ ($C_4H_{10}O$), consisting of two ethyl groups bonded to a central oxygen atom. DEE is seen as a potential alternative fuel or oxygen additive for diesel engines due to its high oxygen content and cetane number. DEE is a liquid at ambient conditions, making it desirable fuel for storage and handling. As seen in Figure 2, DEE is thought to be a renewable fuel because it is made from ethanol through a dehydration process. DEE is also more advantageous than ethanol due to its higher heating value and noncorrosive nature [14].

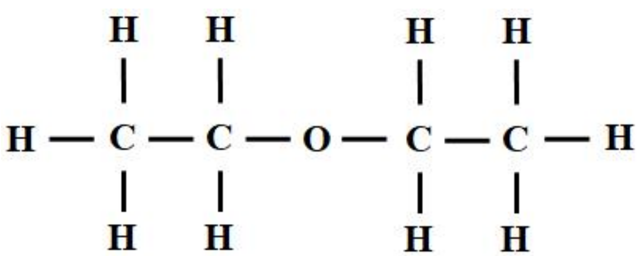


Figure 1. *Chemical composition of diethyl ether [3]*

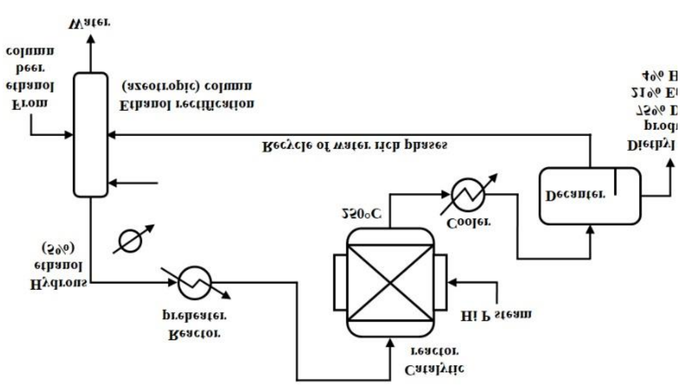


Figure 2. *Production of diethyl ether from ethanol [14]*

Excellent cetane number, appropriate energy density, high oxygen content, low auto ignition temperature, and high volatility are only a few advantageous of DEE, as seen in Table 1. Hence, whether applied as a pure or additive in diesel engines, it can help to increase engine performance and lower emissions and the problem of cold starting [14, 15].

Table 1. *Fuel properties of diesel fuel and DEE [15]*

Property	Diesel	DEE
Chemical formula	C_xH_y	$C_4H_{10}O$
Molecular weight	190–220	74
Density of liquid (kg/L)	~0.84	0.71
Viscosity at NTP* (cP)	2.6	0.23
Oxygen content (wt %)	–	21
Sulfur content (ppm)	~250	–
Boiling temperature (°C)	180–360	34.6
Autoignition temperature in air (°C)	315	160
Flammability limit in air (vol %)	0.6–6.5	1.9–9.5
Stoichiometric air–fuel ratio (AFR_s)	14.6	11.1
Heat of vaporization at NTP* (kJ/kg)	250	356
Lower heating value (MJ/kg)	42.5	33.9
Cetane number (CN)	40–55	125

3. Advantages and Drawbacks of Diethyl Ether

Table 1 lists the fuel properties for DEE along with its advantages and disadvantages. As DEE can be produced from ethanol by using acid catalysts to speed up the dehydration process, it meets the criteria for both biofuel and renewable fuel status. It is claimed that the dehydration of ethanol produces DEE in an inexpensive, consistent, and profitable manner. Furthermore, generating DEE is far less expensive than generating dimethyl ether (DME) [16, 17]. Since DEE is a liquid fuel at room temperature, it can be used as a fuel additive for diesel engines without requiring major modifications. DEE works well as a fuel additive without the need for a solvent because of its high miscibility with most diesel engine fuels. DEE can be utilized with petroleum fuels in internal combustion engines because of its high volatility and low flash point. DEE enhances atomization properties and makes it possible to deliver a consistent fuel–air mixture into the combustion chamber because of its low density and viscosity. Because of the high amount of oxygen in its chemical structure, DEE helps improve combustion, emissions, and engine performance. DEE has a high latent vaporization, which allows it to reduce intake air temperature and boost engine volumetric efficiency. Due in part to its low auto ignition temperature and improved low temperature characteristics, such as a higher cold filter plugging point (CFPP), DEE is an effective ignition enhancer. This facilitates smoother engine operation, particularly in colder climates. DEE increases combustion, engine efficiency, and most engine emissions because of its high cetane number and quick flame speed. However, because of its high volatility and propensity to oxidize and generate peroxides during storage, there are some worries about the influence of DEE on air pollution. To address these issues, antioxidant additives are needed. The high volatility of DEE also makes it difficult to maintain in storage. Another issue with DEE is its higher reactivity in air circumstances and its broader flammability limitations [14]. Because of its decreased calorific value, DEE can increase fuel consumption, particularly at high blending ratios. The low density of DEE can also cause phase separation when it is added to other fuels. DEE's exceptionally low viscosity and lubricity can accelerate injection system wear, making it impossible to use DEE as the only sustainable fuel in diesel engines without changes. The combustion process may be delayed by DEE's lower viscosity, density, and bulk modules and its higher latent heat of vaporization may lessen the peak cylinder pressure and the heat release rate. In the fuel system, the high volatility of DEE might result in vapor lock. In particular, the inadequate fuel volatility and the insufficient fuel distribution among cylinders can result in auto–ignition, detonation, corrosion, and poor engine performance when DEE is utilized at high blending ratios.

4. Findings from Studies on Diethyl Ether

The number of studies was performed on the using DEE in diesel engines and a single cylinder direct injection experimental diesel engines generally were employed at the most of these studies. The parameters such as brake power, torque, engine efficiency, fuel consumption and the emissions of CO, HC, NOx, PM, smoke and CO_2 were monitored and analyzed to assess the impact of DEE on engine performance and emissions in the studies performed. It will be easier to correctly evaluate the results if these researches are categorized based on the fuel types. Accordingly, the studies on DEE can be listed as diesel– DEE blends [18–46], diesel–water–DEE blends [47], diesel–ethanol–DEE blends [48–58], diesel–ferric chloride ($FeCl_3$)–DEE blends [59], diesel–kerosene–DEE blends [60], diesel–acetylene gas–DEE blends [61–62], diesel–biogas–DEE blends [63], diesel–hydrogen–DEE blends [64], diesel–natural gas–DEE blends [65], diesel–toluene–DEE blends [66], biogas–DEE blends [67–68], liquefied petroleum gas (LPG)–DEE blends [69–70], ethanol–DEE blends [71–73], biodiesel–DEE blends [74–109], biodiesel–ethanol–DEE blends [110–111], biodiesel–water–DEE blends [112–113], biodiesel–biogas–DEE blends [114–115], diesel–biodiesel–DEE blends [70, 116–182], diesel–biodiesel–methanol/ethanol–DEE blends [183–187] and diesel–biodiesel–water–DEE blends [188–189]. Here is the summary of the main findings drawn from these studies. Sonawane et al. (2023) found that because DEE has the lower surface tension and dynamic viscosity than diesel, it created smaller droplets when added to the diesel fuel. The addition of DEE to diesel fuel also decreased the spray tip penetration because of the decreased density, surface tension, and viscosity. The addition of DEE aided to diesel the fuel vaporization by the reducing liquid penetration length. Compared to the 40% DEE (DEE40) addition, the 20% DEE (DEE20) addition to diesel demonstrated the higher number of droplets with smaller diameters. While DEE40 addition suggested better evaporation and atomization properties, DEE20 demonstrated greater atomization features. DEE20 caused a lot of smaller droplets to move more slowly, which reduced the axial droplet velocity. The significant changes in the droplet diameter caused by the superior evaporation characteristics of DEE40 produced the more fluctuations than DEE20 [18]. Patil and Thipse (2014) found that the adding DEE to diesel raised the cetane number, volatility, oxygen content, and boiling point while the reducing density, viscosity, and calorific value [19]. Rakopoulos et al. (2012) found that while the brake specific fuel consumption (BSFC) reduced with the DEE–diesel blends, the exhaust gas temperature (EGT) and the brake thermal efficiency (BTE) raised. Additionally, it was shown that while DEE–diesel blends reduced the emissions of smoke, NOx, and CO, they raised the HC emission [20]. Rakopoulos et al. (2013) found that the adding DEE to diesel resulted in a leaner fuel–air mixture, which reduced the maximum cylinder pressure and temperature, delayed the ignition timing, delayed the injection pressure, and reduced the heat losses [21]. Patil and Thipse (2016) found that the adding DEE to diesel raised BTE by 7.96% and NOx emissions by 3.66%, but reduced the emissions of smoke and HC by 12.5% and 15.38%, respectively [22]. Rathod and Darunde (2015) stated that DEE could be used in common rail direct injection (CDI) diesel engines without causing any problems because DEE–diesel blends showed the good performance close to pure diesel [23]. Karthik and Kumar (2016) found that the adding DEE to diesel raised BTE, with the exception of 20% DEE blending ratio. However, because DEE has a lower calorific value than diesel, DEE blends gave the higher fuel consumption than diesel. However, EGT and CO emission was reduced with the rising DEE ratio by the rising exhaust gas recirculation (EGR) while CO_2 emissions were raised [24]. According to Banapurmath et al. (2015), the rising DEE ratio gave a reduction in auto ignition temperature, an increase in latent heat of vaporization, and a greater cetane number. However, it also raised the peak cylinder pressure. The emissions of CO, HC, and smoke were reduced by raising the DEE ratio while BTE and NOx emissions were raised [25]. Lee and Kim (2017) found that although diesel–DEE blends had greater BSFC, the fuel conversion efficiency was equivalent and stable engine operation was achieved. Also, diesel–DEE blends reduced the emissions of HC, CO, and PM, but they raised NOx emissions [26]. Saravanan et al. (2012) found that diesel–DEE blends reduced the ignition delay (ID), combustion duration (CD), and BSFC while rising BTE. Diesel–DEE blends gave the lower NOx and PM emissions but higher CO and HC emissions [27]. Ibrahim (2016) found that the addition of DEE to diesel raised the maximum cylinder pressure and heat release rate (HRR) while decreasing CD. Despite the engine's acceptable stability, the coefficient of variation (COV) raised up to 15% DEE (DEE15) ratio. For DEE15 blend, BTE was raised by 7.2% while BSFC was reduced by 6.7% [28]. Likhitha et al. (2014) found that diesel–DEE blends raised BTE and reduced BSFC. When DEE ratio exceeded 15%, high knocking noises were noticed [29]. Kumar and Nagaprasad (2014) found that when EGR was raised and DEE additive delivered additional oxygen, BTE was raised and BSFC reduced. Also, addition of DEE and diesel particulate filter (DPF) reduced emissions of

CO, HC, NOx, and PM [30]. Balamurugan and Nalini (2016) found that addition of DEE to diesel raised BTE while lowering BSFC and smoke emissions by enhancing combustion [31]. Madhu et al. (2017) found that with 5% DEE (DEE5) blend, BTE and BSFC were raised by 19% and 11%, respectively. The addition of DEE raised CO and HC emissions while decreasing NOx and PM emissions [32]. Cinar et al. (2010) found that cycle–to–cycle changes were extremely small at 10% DEE (DEE10) premixed ratio. 40% premixed DEE (DEE40) ratio gave the audible knocking. EGT, NOx, and soot emissions were lowered up to 23.8%, 19.4%, and 76.1%, respectively. However, premixed DEE raised CO and HC emissions [33]. Yadav et al. (2018) found that when the compression ratio grew, BTE was raised and BSFC was reduced. However, when DEE ratio increased, BTE decreased and BSFC increased [34]. Uslu and Celik (2018) found that when DEE increased, BTE and BSFC decreased while EGT and the emissions of CO, HC, NOx, and smoke reduced. At 7.5% DEE ratio, the maximum increase in BTE was 8%, and at 10% DEE ratio, the maximum increase in BSFC was 10%. The emissions of CO and NOx were reduced to a maximum of 45% and 56% with 10% DEE. Smoke and HC emissions were down 31% and 28% with 7.5% DEE, respectively [35]. Sethi et al. (2020) found that addition of DEE raised the maximum cylinder pressure and temperature. For 15% DEE ratio, BTE increased by 27.1% and BSFC decreased by 15.8%. The inclusion of DEE resulted in an increase in CO_2 and NO emissions but a decrease in EGT, CO, and HC emissions [36]. Iranmanesh et al. (2008) found that adding of DEE decreased the calorific value of the blends and increased their volatility, which enhanced their cold starting ability. By adding DEE to diesel, brake power and BTE increased by 2% and 6.3%, respectively, and CO_2 emissions increased as well. ID, the peak cylinder pressure, BSFC, CO, HC, NOx, and smoke emissions all decreased [38]. Ayhan and Tunca (2018) found that when DEE was added to diesel, BTE increased but BSFC, torque, and brake power dropped. Additionally, there was a drop in emissions of CO, HC, and EGT. The use of DEE resulted in a 12% reduction in smoke and NO emissions [39]. Badajena et al. (2018) found that inclusion of DEE boosted energy conversion efficiency and BTE while decreasing BSFC by 15.8% and raising combustion temperature by 6.8% [40]. Agarwal et al. (2022) found that addition of DEE to diesel led to a minor rise in uncontrolled emissions, including formaldehyde, formic acid, sulfur dioxide, n–pentane, n–octane, and isobutene. Even so, these emissions were still quite low, and with a few little adjustments to equipment or fuel injection technique, they could be made even lower. With DEE blends, a reduced NOx emissions was obtained along with a slightly higher PM emission [42]. Jena et al. (2023) found that compared to conventional diesel combustion (CDC), partially premixed combustion (PPC) demonstrated higher BTE. In comparison to CDC mode, PPC mode had a higher peak cylinder pressure. In comparison to CDC mode, PPC mode had a larger heat release. In PPC mode, DEE–diesel blends showed higher BTE than diesel. At lower loads, 40% DEE addition produced a higher BTE than 20% DEE addition. At lower loads, PPC mode with diesel and DEE blends produced a lower BSFC than CDC mode. Emissions of CO and HC were greater in PPC mode than in CDC mode. In comparison to CDC mode, NOx emissions were 1.5–2 times greater in PPC mode. In PPC mode, DEE blends displayed somewhat more HC emissions than diesel at lower loads [43]. Sun et al. (2023) found that diesel engine running on 0.5% DEE premixed could start up rapidly at −10°C, but that as the ambient temperature dropped, the cold start performance of the engine gradually declined. Diesel was aided in igniting by DEE because the growing DEE ratio allowed the premixed DEE to burn at low intake temperatures. When 2% DEE was premixed, the engine started rapidly and steadily at a very low temperature of about −40°C. When DEE was premixed, lowering the starting fuel injection could cause detonations and speed variations. However, because of the advanced combustion phase, a reduction in the initial fuel supply led to extended speed–up duration during cold start. By delaying the primary injection timing to 2°CA ATDC (after top dead center) for 0.5% DEE premixing and 60% of the basic starting fuel injection quantity, the fastest start was accomplished [44]. According to Swamy et al. (2023), adding DEE increased peak pressure by 2.5% and 1.2% and BTE by 2.5% and 1% in comparison to adding ethanol and butanol. In comparison to ethanol and butanol addition, DEE reduced CO emission by 20% and 11%, HC emission by 17% and 12.2%, and smoke emission by 12.5% and 10.6%. However, DEE increased NOx emissions by 3.6% and 2.4%. Moreover, reductions of 26% and 24.4% in ID and 35.5% and 2.4% in CD were attained [45]. Fayyaz et al. (2023) found that addition of DEE alone increased BSFC by 29.9% compared to addition of manganese (Mn) to diesel. At lower loads, addition of 10% DEE increased torque by 5.4%, 15.4%, and 11.9%; at higher loads, the addition of 250, 375, and 500 mg Mn increased torque by 18.4%, 28.3%, and 23.9%. At lower load, DEE10 addition increased BTE by 4.2, 8.7, and 6.9%; at higher load, 250, 375, and 500 mg Mn increased BTE by 24.2, 28.2, and 26.9%. When 10% DEE was added at a lower load, BSFC decreased by 3.3, 6.8, and 5.7%; however, when 250, 375, and 500 mg of Mn were added at a greater load, BSFC increased by 10.6, 10, and 12.7%. When 10% DEE was added at lower load, CO_2 emissions increased by 11.6, 30.5, and 20.3%; when 250, 375, and 500 mg of Mn were added at higher load, CO_2 emissions increased by 18.4, 28.3, and 23.9%. It was declared that the optimal amounts of DEE and Mn were 10% and 375 mg, respectively [46]. Subramanian and Ramesh (2002) found that adding 10% DEE to water–diesel emulsion increased BTE by 1.9% and decreased CO, HC, NOx, and smoke emissions by 42.8%, 46.7%, and 14.8%, respectively. With addition of DEE, the ID, peak cylinder pressure, and maximum pressure rise rate decreased. The engine's performance was enhanced by the addition of DEE to the water–diesel emulsion, while having no negative impact on smoke or NOx emissions. But under high loads, the emissions of CO and HC were more than those of diesel. Additionally, it was declared that DEE may be used to diesel engines as an additive to address the issues with water–diesel emulsions [47]. Iranmanesh (2013) found that addition of DEE enhanced the properties of diesel–ethanol blend, including distillation, boiling point, oxygen concentration, and ignition quality. DEE proved to be a potent co–solvent in the diesel–ethanol combination. Additionally, the diesel–ethanol blend's volatility increased, which enhanced its cold start capability. With addition of DEE, diesel–ethanol blend's density, viscosity, and heating value all decreased. The addition of DEE to diesel–ethanol blend also enhanced emissions and combustion, resulting in a simultaneous 36.6% reduction in smoke and NOx emissions. 8% DEE addition diesel–ethanol blend was the optimum for performance and emissions with the exception of smoke opacity in which 15% DEE gave the lowest smoke level. For 8% DEE, the minimum HRR, the lowest NOx emissions and the maximum BTE with the rising of a 5.6% were obtained at full load. Also, lowest CO and HC emissions were obtained at 8% DEE ratio [48]. Sudhakar and Sivaprakasam (2014) found that EGT, cylinder pressure, and HRR increased as DEE fumigation ratio with the diesel–ethanol blend increased. At 30% DEE fumigation ratio, there was a 13% increase in HRR. When compared to diesel at 30% DEE fumigation ratio, ID was shortened and cylinder pressure was increased by 3 bars [49]. Sudhakar and Sivaprakasam (2014) found that for 10, 20, and 30% DEE fumigation ratio with diesel–ethanol blend, BTE was increased by 29, 40, and 43% while smoke emission was decreased by 17, 31, and 32%. At high loads, CO and NOx emissions increased by 90% and 48%, respectively. At lower loads, there was 28% increase in HC emission; however, at greater loads, as the DEE fumigation ratio increased, minor fluctuations were recoded. At full load, heavy knocks were observed above the 30% DEE fumigation ratio [50]. Sudhakar and Sivaprakasam (2014) found that adding DEE to a diesel–15% ethanol blend boosted BTE by 15%. Applying EGR also modestly raised BTE. A higher DEE ratio resulted in a drop in ID. The fumigation ratios of 20 and 30% DEE reduced ID by roughly 3°CA. Applying EGR raised ID by roughly 2°CA once more, hence the ideal DEE fumigation ratio was 20% with up to 15% EGR. HRR and the maximum cylinder pressure were lowered by 4% when using 20% DEE fumigation ratio with EGR. The increasing DEE fumigation ratio raised NOx emissions by 49% and EGR reduced NOx emission by 51%. But, HC emission was increased by 33% at initial load and CO emission was increased by 65% at full load. Audible knocking occurred above 30% DEE fumigation ratio at full load [51]. Paul et al. (2015, 2017) found that 5% DEE ratio increased BTE, whereas 10% DEE ratio decreased it. The addition of ethanol to diesel DEE blends resulted in 15.9% increase in BTE and 14.3% decrease in brake specific energy consumption (BSEC). CO, HC, and PM emissions were lowered by 53.1%, 82.9%, and 91%, respectively, when diesel was mixed with 10% DEE and 10% ethanol [52, 53]. Lukhman et al. (2016) found that adding DEE to diesel–ethanol blends enhanced combustion, which increased BTE and decreased total fuel consumption (TFC) as well as CO, HC, NOx, and smoke emissions. The largest drop in TFC was 14%, and the maximum increase in BTE was 20%. CO, NOx, smoke, and CO_2 emissions decreased by 75%, 30%, 10%, and 20%, respectively [54]. Ashok and Saravanan (2007) found that adding DEE to ethanol–diesel blend decreased the ID, EGT, BSFC, maximum pressure rise rate, peak cylinder pressure, and PM emission. It caused 5.5% rise in BTE and 48.9% and 63.2% decrease in smoke and NOx emissions, respectively [55]. Temizer et al. (2022) found that adding ethanol or DEE to diesel decreased the maximum cylinder pressure by around 0.5–3.5%, HRR by approximately 2.3–6.2%, and NO emission by approximately 2–21%. Conversely, adding ethanol to diesel raised the turbulence kinetic energy (TKE) by 0.05%, but adding DEE to the ethanol–diesel blend decreased TKE by 2.7% [56]. Mohebbi et al. (2018) found that diesel–ethanol blends with 40% DEE addition increased the indicated mean effective pressure (IMEP) by 14% and decreased the maximum pressure rise rate by 33%. The higher DEE ratios caused more ID, which led in incomplete combustion and increased CO emission, but the high reactivity of DEE improved fuel oxidation and decreased HC emission. DEE's increased volatility and improved fuel–air mixing qualities enhanced combustion and decreased PM emissions [57]. It was determined by Kumar and Reddy (2015) that DEE addition to ethanol–diesel blends raised BTE and HC emission, while it reduced CO and CO_2 emissions [58]. Patnaik et al. (2017) found that adding $FeCl_3$ to diesel raised the peak pressure and temperature in the cylinder. $FeCl_3$ addition resulted in 8% rise in BTE as well as an increase in NO and CO_2 emissions. However, BSFC was decreased by 9%, and addition of $FeCl_3$ also decreased the emissions of smoke, HC, and CO. However, diesel–$FeCl_3$ blend with 15% DEE addition had the highest BTE, the lowest BSFC, and the lowest emissions of smoke, HC, CO, and CO_2 [59]. Patil and Thipse (2015) found that DEE was completely miscible in kerosene and diesel fuel. when the DEE ratio raised in diesel and kerosene blends, the oxygen content and cetane number raised while the density, kinematic viscosity, and calorific value decreased. Blends of DEE, kerosene, and diesel demonstrated superior performance in terms of BTE, BSFC, smoke emission at full load, and half load emissions. Additionally, they reported generally lower NO, nearly same CO, higher HC at full load, and lower HC at part load emissions [60]. Mahla et al. (2012) found that while diesel–acetylene gas dual fuel operation improved BTE and brake power without compromising BSFC up to a 20% DEE ratio, performance declined and engine knocking began afterwards. The addition of acetylene to diesel–DEE blends increased BTE and brake power while lowering EGT, BSFC and smoke emission. With 20% DEE, diesel–acetylene gas operation produced the highest BTE and lowest BSFC [61]. Raman and Kumar (2022) found that BTE increased by 1.7% at 80% load with diesel and acetylene gas dual fuel operation with 10% DEE. With 10% DEE and diesel–acetylene gas at

80% load, the emissions of HC, CO, NOx, and smoke were decreased by 27%, 45%, 22%, and 43%, respectively. For 10% DEE blend in dual fuel mode, the cylinder pressure, peak heat release rate, and ID were increased [62]. Mishra et al. (2024) found that in the diesel–biogas dual fuel mode with 5% DEE addition, HRR was delayed and the peak cylinder pressure was raised. In the case of a 0.8 kg/h biogas addition to diesel with 5% DEE at full load, BTE decreased by 12.7% and 5.2% while BSEC increased by 14.3% and 9%. When 5% DEE was added to diesel–biogas dual fuel low heat rejection engine, the emissions of CO and HC increased but smoke and NOx emissions decreased [63]. Barik et al. (2024) found that the best performance, combustion, and emissions were obtained with diesel, 20% DEE and H_2. For 20% DEE and H_2 with diesel at full load, CD and ID were reduced by 9% and 20.8%, respectively. In addition, at maximum load, 20% DEE and H_2 with diesel increased BTE by 0.6% and decreased BSFC by 3.7%. For 20% DEE and H_2 with diesel at full load, the emissions of HC and CO were lowered by 35% and 29.6%, whereas the emissions of NO and CO_2 were increased by 29.4% and 17.4% [64]. It was determined by Karabektas et al. (2014) that diesel–natural gas dual fuel operation had negative effect on the engine performance at low and medium loads while it improved the performance at high loads. The dual fuel operation gave lower NO emission at low and medium loads while it served the higher NO emission at high loads. The emissions of CO and HC were raised at low and medium loads while these emissions were reduced with dual fuel operation at high loads. However, the addition of DEE as pilot fuel in dual fuel mode reduced BSEC and raised BTE. Additionally, DEE addition reduced NO and CO emissions at all loads and the higher DEE addition also provided better performance and emissions compared to diesel–natural gas dual fuel operation [65]. It was determined by Ozer and Vural (2024) that the emissions were reduced with toluene and DEE addition to diesel and the reduction was continued with H_2, H_2+HHO and H_2+HHO+O_2 gas fuels addition to diesel–toluene–DEE blends. The addition of O_2 also increased the combustion efficiency and decreased the emissions. The addition of toluene improved BSEC by 1% while DEE addition increased BSEC by 0.75%. The increasing O_2 in the gas fuels with toluene or DEE reduced BSEC and the highest drop in BSEC was obtained with toluene mixtures. BTE was increased with adding gas fuels and highest increase in BTE was achieved with O_2 addition. The emissions of CO, HC and smoke were reduced with all tested blends and the highest reduction was obtained with highest O_2 addition. NOx emission was increased with all the fuel blends and the highest increase in NOx emission was gained with the highest amount of O_2. The use of H_2 reduced CO_2 emission, but the increase of O_2 raised CO_2 [66]. Sudheesh and Mallikarjuna (2010) found that using biogas in homogeneous charge compression ignition (HCCI) mode with DEE produced higher BTE at all loads. In comparison to biogas and diesel dual fuel operation and biogas spark ignition (SI) modes, BTE raised by 3.48 and 9.21% for biogas with DEE in HCCI mode, respectively. Additionally, for HCCI mode, there were very little emissions of NO and smoke, and less than 0.4% of CO. Comparing HCCI mode to biogas SI mode, HC emission was similarly reduced [67]. Mishra et al. (2023) found that port fuel injection method outperformed manifold injections in terms of BTE. Emissions of NOx and smoke were decreased by the manifold injections. By decreasing knock and somewhat lowering BTE, the rising biogas flow rate increased the maximum operational load limit [68]. Jothi et al. (2007) found that when compared to pure diesel, LPG–DEE blends decreased the cycle pressure, EGT, BTE, and NO emission by 23% and 65%, respectively, at full load. In comparison to diesel fuel, the highest reduction in smoke and PM emissions was 85% and 89%, respectively. Nonetheless, the LPG–DEE blends significantly increased the emissions of CO and HC [69]. Dora and Jothi (2019) found that as compared to diesel at 70% load, LPG–DEE operation decreased BTE by 26% and NOx emission by 30%. However, compared to diesel fuel, CO emissions from LPG–DEE blends were greater [70]. It was determined by Polat (2016) that HCCI combustion was achieved by even leaner mixtures with increasing DEE ratio, since DEE provided earlier combustion by acting as ignition improver. The peak cylinder pressure and BTE were increased with increasing inlet air temperature. The cylinder pressure, heat release rate and knocking tendency were increased with reducing fuel–air equivalence ratio (lambda) while BTE was decreased. 30% ethanol and 70% DEE blend gave the highest BTE. The increasing inlet air inlet temperature, lambda and DEE ratio reduced CO and HC emissions while almost zero NOx was obtained for all tested blends [71]. Prante et al. (2023) found that because DEE has a low boiling point and low viscosity, there can be some operational challenges when adding it. As a result, ethanol–DEE blends boosted BSFC while lowering brake power and BTE. But by modifying the fuel quantity and injection timing using a high pressure common rail injection system, DEE addition produced superior performance [72]. Mack et al. (2015) found that adding DTBP to ethanol–DEE blends affected the start of combustion more than adding DTBP to ethanol alone. For the earlier combustion timings, full combustion of ethanol was made possible by the addition of DTBP to ethanol–DEE blends; this was not possible for fuel blends of ethanol–DEE without DTBP [73]. It was determined by Subhash et al. (2023) that 5% DEE addition to biodiesel and biomix blend reduced the density about 0.3–0.6%, viscosity about 18.2–18.5%, flash point about 1.2–3.6%, acid value about 9.6–17.2%, iodine number about 11.9–12.2%, free fatty acid about 10.9–12.2% and heating value about 0.2–3.8%, while it raised the cetane number about 6.7–6.9% and oxidation stability about 19.1–35.2% [74]. According to Zapata–Mina et al. (2022), for the lambda between 2.1 and 2.2 the maximum BTE produced when 40% DEE and 60% fusel oil biodiesel blend were used; nevertheless, the performance of the HCCI engine was decreased as the DEE ratio increased. Using 80% DEE and 20% fusel oil biodiesel resulted in increased engine stability.

With an 80% DEE blend, there was an increase in exergy destruction between lambda 3.4 and 3.9. With 40% DEE and 80% DEE blends, the maximum and lowest exergy efficiency was achieved [75]. It was determined by Gurusamy et al. (2024) that addition of 8L/min hydrogen to intake manifold with Jatropha and Camphor oils increased BTE and the maximum BTE reached up to 33.7% at full load. Similarly, the maximum values of the cylinder peak pressure, heat release rate, exergy efficiency and sustainability index were 76.5 bar, 53.9 J/°CA, 43% and 1.73 with H_2 addition. The reductions in CO, HC, CO_2 and smoke emissions were noted with the rising NO emission. Further, 20% DEE addition to Jatropha and Camphor oils and 8L/min H_2 induction reduced BTE and a similar trend was noted in the emissions of CO, HC, NO and smoke. However, 10% DEE addition to Jatropha and Camphor oils with 8L/min H_2 resulted in increase in BTE and the maximum value of BTE was 34.2% [76]. Ergen (2024) found that adding DEE to biodiesel boosted BTE and engine output, but increased NO emissions as compared to diesel fuel. The optimal outcome was achieved with a 5% blend of DEE; this DEE ratio reduced NO emissions by 13% and boosted engine power by 5.7%. The combination of 10% EGR and 5% DEE–biodiesel blend produced the greatest results for engine performance and NO emission. In comparison to diesel, this combination decreased torque by 3% and NO emissions up to 70% [77]. It was determined by Raman and Roy (2023) that the maximum dissolution of expanded polystyrene (EPS) was 10 g/L in pure biodiesel and the biodiesel kinematic viscosity was raised by 23% for 10g/L EPS. The advances in EPS dissolution, performance and emissions were noted with DEE addition. The reduction in BSFC and increment in BTE was by 10% with only DEE addition while this was 7% for 10g/L EPS and DEE addition. 10% DEE and 10 g/L EPS addition reduced CO, HC and NOx with 22%, 38% and 1.25% and smoke also reduced while only EPS infusion significantly increased these emissions [78]. Kasiraman et al. (2011) found that at full load, 30% DEE blend produced a similar BTE and HRR to diesel fuel. Diesel had a BTE of 30.1% and 30% DEE blend of 29.7%. When 30% DEE was added to cashewnut shell oil biodiesel, the peak cylinder pressure and rate of maximum pressure rise raised, but ID and CD were lowered by 2°CA and smoke and NO emissions were reduced by 5% and 1.7%, respectively [79]. Pranesh et al. (2015) found that adding 25% DEE to cotton seed oil biodiesel boosted BTE by 6.6% and decreased CO, HC, and NOx emissions by 74%, 6.9%, and 45.7%, respectively [80]. Rakopoulos (2013) found that adding n–butanol and DEE to vegetable oil, or its biodiesel, enhanced engine performance and emissions without any solvent or stability issues during engine operation. The inclusion of DEE and n–butanol resulted in a decrease in BSFC and an increase in BTE. For every combination that was tested, the emissions of HC increased while the emissions of CO, NOx, and smoke decreased. Blends of DEE performed marginally better than blends of n–butanol [81]. Rakopoulos et al. (2016) found that although the cyclic variations were within acceptable limits, they were slightly larger for blends of n–butanol and DEE because of the higher ID. Because of the additional oxygen, the addition of n–butanol and DEE to cotton seed oil biodiesel decreased the emissions of smoke and NOx; nevertheless, the use of the n–butanol and DEE blends increased the emissions of HC while reducing CO emission [82]. Rakopoulos et al. (2014) found that adding ethanol, n–butanol, and DEE to cotton seed oil biodiesel resulted in delayed injection time, decreased ID and EGT, and increased cylinder pressure. The blends of ethanol, n–butanol, and DEE resulted in a decrease in CO, NOx, and smoke emissions but an increase in HC emissions. Additionally, adding ethanol, n–butanol, and DEE to cotton seed oil biodiesel enhanced BTE and BSFC [83]. It was determined by Krishna et al. (2014) that fuel consumption was reduced with rising DEE ratio from 5% to 25% from 56.09 g/min to 51 g/min compared to 55 g/min for karanja oil and 44 g/min for diesel. BTE was 26.73% for 25% DEE with karanja oil, 23.21% for karanja oil and 27.01% for diesel. CO emission was 0.045% for 25% DEE with karanja oil, 0.055% for karanja oil and 0.035% for diesel. NOx emission was 265 ppm for 25% DEE with karanja oil, 347 ppm for karanja oil and 488 ppm for diesel. HC emission was 27 ppm for 25% DEE with karanja oil, 44 ppm for karanja oil and 29 ppm for diesel [84]. It was determined by Singh and Sahni (2015) that DEE addition to biodiesel slightly reduced both BTE and BSFC at the same load condition [85]. Jawre and Lawankar (2014) found that as injection pressure increased, engine performance increased as well, and mixtures of biodiesel and DEE performed better than pure biodiesel. For 15% DEE blend, BTE was higher at 190 bars of injection pressure but decreased at 170 bars. Compared to 10% DEE blend, 5% DEE blend, and biodiesel, 15% DEE blend produced lower BSFC. At higher engine loads, smoke emission was reduced with all DEE blends [86]. Samraj et al. (2023) found that adding 15% DEE (DEE15) to light fraction waste cooking oil biodiesel produced the best outcomes in terms of emissions and performance. Compared to diesel at full load, the BSFC for DEE15 was higher by 28.9%, BTE was lower by 7.6%, and EGT was lower by 11.9%. When compared to diesel at full load, the emissions of HC, CO, and smoke were lower by 32.9%, 25%, and 29.4%, respectively, while NO emission were higher by 36% [87]. It was determined by Górski et al. (2020) that DEE addition to biodiesel reduced the viscosity, density and surface tension and improved low temperature properties of biodiesel. 10% and 30% DEE blends reduced viscosity by 53% and 82% and 30% DEE blend also reduced the density and surface tension up to 6% and 25%. The cold filter plugging point (CFPP) was improved by DEE addition and 30% DEE blend reduced CFPP up to −24°C. Hence, DEE blends seem valuable in coldest seasons. Linseed oil biodiesel showed the worse performance than diesel. However, these disadvantages could be reduced with DEE addition. The combustion of DEE blends was similar to diesel. 20% DEE blend reduced smoke emission to level of diesel fuel [88]. Rao and Reddi (2016) found that adding 15% DEE (DEE15) to mahua oil biodiesel increased BTE and improved BSFC. At full load, the emissions were also significantly reduced by DEE15 [89]. According to Babu et al. (2012), adding 15% DEE (DEE15) to mahua oil biodiesel increased BTE and improved BSFC. At low and medium loads, the addition of DEE decreased NOx emissions; however, at high loads, DEE blends produced higher NOx emissions than diesel and lower NOx emissions than biodiesel. With the addition of DEE, there was a little decrease in smoke emissions and a reduction in NOx emissions of more than 10%. At full load, DEE15 decreased the smoke emission. At full load, DEE15 reduced CO emissions by 67%, however HC emissions grew steadily until 15% DEE ratio [90]. Sivalakshmi and Balusamy (2013) found that adding 5% DEE to neem oil biodiesel boosted HRR and peak cylinder pressure. Smoke and CO emissions decreased with all blends at all loads, however NOx and HC emissions increased when using DEE5 blend at maximum load. Additionally, BTE of 5% DEE blend was higher than biodiesel [91]. Senthil et al. (2015) found that adding ethanol, DME, and DEE to nerium oil biodiesel enhanced BTE at all loads. At all loads, the addition of DME, DEE, and ethanol resulted in reduced emissions of smoke and CO. When DME, DEE, and ethanol were added to nerium oil biodiesel at all loads, the levels of HC and NOx increased [92]. It was determined by Purushothaman and Nagarajan (2009) that the peak cylinder pressure and HRR were higher for orange oil–DEE blend than diesel–orange oil blend. BTE was higher by 3% and 1.2% for orange oil–DEE blend and orange oil–diesel blend than diesel. NOx emission was lower for orange oil–DEE blend and higher orange oil–diesel blend compared to diesel. CO emission was raised by 76% with orange oil–DEE blend and reduced by 7.6% for orange oil–diesel blend compared to diesel at full load. HC emission was higher for orange oil–DEE blend and lower for orange oil–diesel blend compared to diesel. Smoke emission was lower for orange oil–DEE blend and orange oil–diesel blends than diesel [93]. It was determined by Purushothaman and Nagarajan (2010) that 36 mg/s DEE addition gave the best combustion, performance and emission results. BTE was raised by 3% for 36 mg/s of DEE with orange oil compared to diesel at full load. The emissions of HC and CO were raised by 0.22 g/kWh and 8.8 g/kWh for 36 mg/s DEE with orange oil at low load and 0.01 g/kWh and 0.93 g/kWh at full load compared to diesel. The emissions of NOx and smoke were reduced by 8% and 4.7% at full load for 36 mg/s of DEE with orange oil compared to diesel. The peak cylinder pressure and heat release rate were higher by 7 bars and 15 J/°CA for 36 mg/s DEE with orange oil than diesel at full load [94]. Ali et al. (2009) found that as DEE ratio increased in palm oil biodiesel, the density and viscosity decreased. The inclusion of DEE enhanced the acid value and pour point as well, but the cloud point and energy content of the DEE–biodiesel blends did not significantly change. When compared to pure biodiesel at 8% DEE ratio, the reduction in heating value was 4.7% and the maximum pour point was 7°C [95]. Ali et al. (2014) found that besides a minor drop in energy content, adding ethanol, butanol, and DEE to palm oil biodiesel enhanced its acid value, density, viscosity, pour point, and cloud point. At a 5% DEE ratio, the pour point was reduced by a maximum of 5°C. The addition of 5% ethanol, butanol, and DEE resulted in a reduction of viscosity of 12%, 7%, and 16.5%. When compared to pure biodiesel, the addition of DEE, butanol, and ethanol to palm oil biodiesel also increased BSFC and brake power; the highest results were obtained with the addition of DEE [96]. It was determined by Kumar and Prasad (2014) that 30% DEE addition to palm oil biodiesel gave the best engine performance. However, 50% DEE blend was not tested, as the engine speed was fluctuated and temperature of engine reached to so high; hence engine cannot run by this blend [97]. Rajan et al. (2016) found that when DEE was added to pongamia oil biodiesel at full load, ID, maximum pressure rise rate, peak pressure, and HRR all decreased. At full load, BTE increased by 3.1% and 6.3% with 15% DEE blend and 3.7% less with diesel and 10% DEE blend and biodiesel, respectively. With 15% DEE blend, smoke and CO emissions were down 27% and 10%, respectively, although HC emissions were up when compared to diesel at full load. In addition, at full load, 15% DEE blend greatly decreased smoke and NO emissions by 32% as compared to biodiesel [98]. Górski et al. (2023) found that while the coefficient of variability of indicated mean effective pressure (COV of IMEP) for DEE blends did not surpass 4%, the increasing DEE ratio in rapeseed oil biodiesel led to excessive irregularity in engine operation when compared to diesel. Vapor locks, which resulted from DEE evaporating in the fuel line and stopping the fuel injector from operating, were the cause of the combustion degradation [99]. Lotko et al. (2018) found that the biodiesel–DEE blends characteristics were comparable to those of diesel. The viscosity, surface tension, and density of the rapeseed oil biodiesel were all decreased by the addition of DEE. Consequently, adding DEE to biodiesel could increase the fuel's quality and combustion. In comparison to pure biodiesel, the addition of DEE to the biodiesel decreased smoke output by 50% [100]. Smigins and Zakis (2020) found that adding DEE to rapeseed oil biodiesel decreased engine power by 6.2–17.3% and increased BSFC by 0.6–15.5% when compared to the biodiesel. All DEE blends showed the lower emissions of HC and NOx, but higher emissions of CO and CO_2 when compared to the biodiesel. With 20% and 30% DEE blends, NOx emissions were roughly 24% lower than that of the biodiesel [101]. Geo et al. (2010) found that BTE increased by 7.5% by using rubber seed oil biodiesel with 200g/h DEE injection into the intake air when instead of pure biodiesel, whereas it decreased by 4.7% when using diesel. When 200g/h DEE injection was used instead of biodiesel, smoke emission was decreased by 34.4%, although it was still 15% higher than that of diesel. The injection of DEE also decreased the emissions of CO and HC. When 200g/h DEE was injected instead of biodiesel, NOx emissions were decreased by 13.1%, although they were still greater 34.8% than that of diesel. In comparison to biodiesel, DEE injection increased the peak cylinder pressure and pressure rise rate while lowering ID and CD [102]. Danesha and Manjunath (2016) found that while BTE was comparable to diesel, BSFC was decreased by adding DEE to simarouba glauca seed oil biodiesel. CO, HC, and NOx emissions decreased, while CO_2 emissions increased when DEE was added [103]. Górski et al. (2022) found that adding DEE to sunflower oil biodiesel improved atomization during injection into the combustion chamber and decreased the viscosity, density, and surface tension. The low temperature qualities were further enhanced by the inclusion of DEE, suggesting that the DEE blends might be used during the winter seasons. DEE inclusion lowered the flash points, ensuring the safety of transportation. When a sufficiently high concentration of DEE was added to the biodiesel, the combustion of DEE blends was comparable to that of diesel. Closer to diesel smoke levels were obtained with 30% DEE addition. DEE blends of HC and NOx emissions were comparable to those of diesel fuel [104]. Hariharan et al. (2013) found that the DEE blend of ID was longer 2.8°CA than that of diesel. By using 130 g/h DEE with tire pyrolysis oil biodiesel instead of diesel at full load, the peak cylinder pressure increased by 3 bars. BTE was decreased by 2.5 percent when DEE was added at full load instead of diesel. When utilizing of DEE blend instead of diesel, NOx emissions were decreased by 5%. In comparison to diesel, the DEE blend had 2%, 4.5%, and 38% more emissions of HC, CO, and smoke [105]. It was determined by Patil and Rao (2018) that engine performance of waste cooking oil biodiesel with 15% DEE and 10% EGR was comparable with diesel fuel. The rising EGR reduced BTE and NOx emission [106]. Devaraj et al. (2015) found that waste plastic pyrolysis oil (WPPO) has properties comparable to diesel and could therefore be used in diesel engines without modification. DEE addition to WPPO improved the fuel atomization and decreased viscosity, which improved BTE. 10% DEE produced a greater BTE than 5% DEE. At full load, BTE was greater than WPPO by 10% DEE. HRR and the peak cylinder pressure were lowered by the increasing DEE ratio. Diesel had less brake power than WPPO, and DEE blends had less brake power than WPPO. When DEE was added to WPPO biodiesel, the emissions of CO and NOx were reduced, but the emissions of HC were increased [107]. Kaimal and Vijayabalan (2016) found that when DEE ratio increased in waste plastic oil biodiesel, BTE decreased and BSEC increased. In comparison to diesel and biodiesel, DEE blends slowed down the combustion and decreased peak cylinder pressure and HRR. Additionally, adding DEE decreased smoke and NOx emissions by 25% and 29%, respectively at maximum load. CO emissions decreased with DEE blends but HC emissions increased. 15% DEE blend produced decreased emissions and improved combustion and performance [108]. Wiangkham et al. (2023) found that adding DEE to waste plastic oil biodiesel decreased the density, gravity, flash point, and viscosity while increasing their cetane index. At low loads, engine performance decreased with DEE blends at high loads by shortening ID. However, DEE addition produced earlier combustion; increased DEE ratio did not produce more advanced combustion. The amount of NOx emissions decreased at high loads with DEE addition, while the emissions of CO and HC remained relatively constant. It was declared that the best DEE ratio for the highest BTE and lowest NOx emission was between 10% and 14% [109]. Carvalho et al. (2020) found that BTE was consistent across all evaluated fuels and loads. In comparison to diesel, the biodiesel increased CO emissions by 20%, NOx emissions by 1%, and HC emissions by 1%. Because biodiesel with 20% ethanol has larger oxygen content and a lower cetane number, it also produces more NOx emissions. In comparison to biodesel and diesel, this combination also increased the emissions of CO and HC. The addition of DEE to the biodiesel–ethanol blend resulted in a 37% increase in HC emissions and 3–13% decrease in NOx and CO emissions, respectively. Additionally, BTE was increased at moderate and high loads using a biodiesel–ethanol blend with DEE addition [110]. Venu and Madhavan (2016) found that adding titanium oxide (TiO_2) or zirconium oxide (ZrO_2) improved combustion while producing the lower pollutants. In comparison to biodiesel–ethanol blend, the addition of TiO_2 increased NOx, HC, and smoke emissions while reducing BSFC and CO emission. In contrast, the addition of ZrO_2 increased BSFC and HC emissions while reducing CO, CO_2, and smoke emissions. Conversely, the addition of DEE increased HRR and the emissions of CO and HC while lowering BSFC and the emissions of NOx, and smoke. The simultaneous decrease in smoke and NOx showed how DEE affected low temperature combustion (LTC) [111]. Satyanarayanamurthy (2012) found that the water–DEE solution produced micro–explosions during combustion, which led to better diffused combustion and decrease in peak cylinder pressure. At full load, 15% water–DEE solution with biodiesel increased BTE by 2%. More than 20% water DEE infusion was required before the crank case oil dilution began. When water–DEE ratio increased from 5% to 15%, the amount of NO emissions was lowered by 500 ppm. HC emission produced by 15% water–DEE was nearly identical to that of pure diesel [112]. Sachuthananthan and Jeyachandran (2007) found that when compared to other blends and water–biodiesel emulsion, 15% DEE blend performed better and produced lower emissions. At full load, BTE was raised from 28.3% to 29% with 15% DEE blend. At full load, 15% DEE blend decreased CO emission from 0.175% to 0.1% and HC emissions from 75 ppm to 40 ppm. Diesel had smoke emission of 4.2 BSU (Bosch Smoke Units), biodiesel had 4.5 BSU, and water–biodiesel emulsion had 2.5 BSU. With 15% DEE blend; the emissions of smoke were decreased to 1.6 BSU. 10% DEE blend had NOx emission levels of 568 ppm, whereas 30% water–biodiesel emulsion had NOx emission levels of 651 ppm [113]. It was determined by Barik and Murugan (2016) that karanja oil biodiesel–biogas dual fuel operation with 4% DEE gave the better combustion, performance and emissions. 4% DEE injection raised BTE by 2.3% and reduced BSFC by 5.8%

compared to the dual fuel operation at full load. The emission of CO, HC and smoke were reduced by 12.2%, 10.6% and 5.7% with %4 DEE at full load. But, NO emission was higher 12.7% with %4 DEE compared to dual fuel operation; it was lower 10.9% than biodiesel at full load [114]. It was determined by Barik et al. (2017) that BTE was raised by 7.1% and BSFC was reduced 2.2% with karanja oil biodiesel–biogas dual fuel operation with DEE addition compared to biodiesel. The emissions of CO, HC and smoke were reduced by 42.2%, 39.5% and 42.8% at full load compared to diesel. But, NO emission was higher 7.6% than that of diesel, but it was 1.2% lower than that of biodiesel at full load [115]. Nanthagopal et al. (2019) found that all tested DEE blends had reduced the combustion characteristics. In comparison to pure diesel, the addition of DEE to the diesel–biodiesel blend increased BSFC by 12.5% and decreased BTE by 5.3%. The emissions of HC, CO, NOx, and CO_2 were reduced by 84%, 4.6%, 57%, and 5.2%, respectively with DEE blends at full load. With 12.5% DEE blend, smoke output increased to 80.1% [116]. Jeevanantham et al. (2019) found that adding 5% DEE to diesel–biodiesel blend increased BTE by 5.3% as compared to diesel. The addition of 5% DEE and 5% MTBE (Methyl tert–Butyl Ether) to the diesel–biodiesel blend decreased CO emissions by 8.1% and 14.8%, respectively. When added to a diesel–biodiesel blend, 10% MTBE and 10% DEE decreased NOx emissions by 8.8% and 32%, respectively, when compared to diesel at full load. With the addition of MTBE and DEE, the emissions of smoke and HC also decreased [117]. Dora and Jothi (2019) found that the addition of DEE to the diesel–biodiesel blend had no appreciable effect on engine performance. However, adding 2% DEE to blend of 80% diesel and 20% biodiesel resulted in an apparent drop in emissions. DEE blends shown a significant decrease in CO and NOx emissions [70]. It was determined by Prabakaran et al. (2022) that rising DEE ratio in diesel–biodiesel blends reduced calorific value, cetane number, viscosity and flash/fire point, but it increased density and cloud/pour point. Cetane values of DEE blends were higher than biodiesel, but cetane values were lower by 5.46%, 8.2% and 10.9% than diesel. HRR of 20, 30 and 40% biodiesel–diesel blends were lowered by 15.6%, 12.1% and 8.6% and this reduced the maximum cylinder pressure and temperature. Brake power of 40% biodiesel–diesel blends was similar to diesel, but it was lower 3.8% and 2.2% for 20% and 30% biodiesel–diesel blends. BTE of 40%, 30% and 20% biodiesel–diesel blends were lower 2%, 7.4%, and 11.3% than diesel. The emissions of CO and HC were reduced by 17–35% and 13–25% with DEE blends, while CO_2 emission was almost equal for all DEE blends. But, DEE blends emitted 11–19% more NOx emission than diesel [118]. Shinde and Yadav (2016) found that adding DEE to diesel–biodiesel blend increased the oxygen content and cetane number while decreasing the calorific value, density, and viscosity. DEE added to the diesel–biodiesel blend also enhanced BTE and BSFC with reduced emissions. DEE addition up to 15% ratio did not require any changes, but for improved performance and emissions, more than 15% DEE did [119]. It was determined by Pillai et al. (2023) that rising DEE addition to diesel–biodiesel blends improved BTE and BSFC with reduced the emissions of CO, HC, NOx and CO_2 [120]. Krishnamoorthi and Malayalamurthi (2017) found that when DEE was added to the diesel–biodiesel blend at full load for a CR of 17.5 and a number of nozzle holes of 5, BTE was higher by 4.3% and the NOx emission was decreased by 3.9%. The inclusion of DEE and increase in nozzle holes led to decrease in BSEC, HC, CO, and smoke emissions while increasing BTE and CO_2 emissions [121]. Kuberan and Alagumurthi (2017) found that adding DEE to diesel–biodiesel blend improved combustion, increasing BTE and lowering BSFC. When DEE was added, emissions of CO, HC, and NOx were also decreased [122]. It was determined by Chandirasekaran and Senthilkumar (2023) that smoke opacity was reduced by 14.3% and 3.6% for 5% DEE addition to diesel–biodiesel blend compared to pure diesel and biodiesel, besides improved engine performance [123]. According to research by Alruqi et al. (2023), at 220 bar injection pressure, 90% engine load, and 15% DEE addition to diesel–biodiesel blend, the maximum BTE and minimum BSFC were found to be 27.91% and 329g/kWh, respectively. Comparing 15% DEE blend to 20% biodiesel–80% diesel combination, BSFC was 13.54% lower. In comparison to 20% biodiesel–80% diesel blend, NOx emissions were likewise reduced with 5% DEE blend; however, they were higher with 15% DEE blend. In comparison to diesel, HC and CO emissions were likewise decreased by 29.65% and 6.89% using 15% DEE blend [124]. Ahmed et al. (2023) found that adding 20% DEE to diesel–animal fat biodiesel blend increased the cylinder pressure while lowering EGT. In comparison to blend of diesel and 20% biodiesel and diesel, 20% DEE addition produced BSFC that was 4.8% higher and 1.4% lower. In comparison to diesel, BSEC was greater for 20% DEE, 10% DEE, and 20% biodiesel–diesel blends by 1.93%, 8.5%, and 5.6%, respectively. In comparison to diesel, BTE was reduced by 7.1% and 9.3% with blends of 20% and 10% DEE, respectively. When comparing 20% DEE blend to diesel, the emissions of CO, HC, and NOx were decreased by 37.8%, 50.7%, and 4.18%, respectively. However, the emission of smoke increased by 20.8% [125]. It was determined by Gurusamy and Ponnusamy (2023) that DEE addition to diesel–campor fat biodiesel blend reduced the cylinder pressure and temperature, but hydrogen induction raised them. The rising hydrogen induction raised BTE, but rising DEE reduced BTE. The lowest CO emission was 0.111% for hydrogen induction without DEE, but it was reduced to 0.101% with 10% DEE addition then it raised by 20% DEE addition at full load. The lowest HC emission was 86 ppm for hydrogen induction without DEE, but it reduced by 10% DEE addition at all loads and it raised by 20% DEE addition. CO_2 emission was reduced with hydrogen induction, but it was higher by 10% DEE addition than 20% DEE addition. Smoke emission was lower with 10% DEE addition at full load than the other blends [126]. It was determined by

Kumar et al. (2015) that rising biodiesel ratio reduced performance. 90% diesel–10% cashew nut shell oil biodiesel blend gave closer performance to diesel, but 30% and higher biodiesel blends gave poor result. 20% biodiesel blend was the best and so it was blended with DEE at ratios of 5, 10 and 15%. 15% DEE blend gave the 26.5% of BTE which was close to that of diesel. 15% DEE blend emitted 1200 ppm of NOx while it was 1195 ppm for diesel, but 20% biodiesel blend emitted 1450 ppm of NOx. DEE addition reduced NOx up to 17% compared to 20% biodiesel blend. CO emission was also reduced by DEE addition. Smoke emission was 3.96, 3.38, 3.15 FSN (filter smoke number) for 20% biodiesel blend, 15% DEE blend and diesel [127]. It was determined by Kumar et al. (2017) that 80% diesel–20% cashew nut shell oil biodiesel blend reduced engine performance. BTE of 20% biodiesel blend was 27.52% while it was 29.73% for diesel. However, DEE addition to 20% biodiesel blend improved further BTE; it was 28.96% for 10% DEE blend which was very close to that of diesel. 20% biodiesel blend reduced smoke and CO_2 emissions, but it increased HC and NOx emissions. DEE addition to 20% biodiesel blend reduced HC, NOx and smoke emissions. HC emission was 30, 34, 29 and 23 ppm for diesel, 20% biodiesel, 10% DEE and 15% DEE. NOx emission was 1195, 1450, 1511, 1327, 1373 and 1200 ppm for diesel, 20% biodiesel, 30% biodiesel, 5% DEE, 10% DEE and 15% DEE. DEE addition to diesel–biodiesel blend also reduced NOx emission by 9.94% compared to 20% biodiesel blend. Smoke emission was 3.96, 3.38, 3.15 FSN for 20% biodiesel, 15% DEE and diesel [128]. Ganesha and Chethan (2016) found that the blend of 90% diesel and 10% cashew nut shell oil biodiesel had performance and combustion characteristics similar to that of diesel, with reduced emissions of CO and NOx. However, the addition of DEE increased the amount of HC emissions [129]. Pushparaj et al. (2014) found that cetane number, calorific value, sulphur level, and flash point of cashew nut shell oil biodiesel were superior to those of diesel. Density and viscosity of the diesel–biodiesel blend were enhanced by the addition of DEE. Compared to 20% biodiesel blend, 10% DEE blend decreased HC and NO emissions by 34.6% and 69.4% at full load. When using blend of 20% biodiesel and diesel, there was 17% reduction in smoke emission [130]. It was determined by Senthilkumar et al. (2023) that the higher total fuel consumption (TFC) was aroused with 90% diesel–10% cashew nut shell oil biodiesel blend than diesel for fuel injection pressure (FIP) of 190 bars. DEE addition to 10% biodiesel blend reduced TFC at FIP of 210 and 230 bars. DEE addition to 10% biodiesel blend also raised mechanical efficiency (ME) of 10% biodiesel blend by improving the combustion. The optimum results were obtained as TFC of 845 g/h and ME of 68.1% with 15% DEE (DEE15) blend at FIP 190 bar. 5% DEE (DEE5) blend also produced TFC of 915 g/h and ME of 71% at optimized FIP of 230 bars. The rising of FIP and DEE addition improved ME with a little increase in TFC for 10% biodiesel blend [131]. Senthilkumar and Murugesan (2023) found that combustion temperature and NOx emission were decreased by higher latent heat of vaporization and lower calorific value of DEE. At full load, 10% DEE addition to 90% diesel–10% cashew nut shell oil biodiesel blend resulted in a 71% reduction in NOx emissions. DEE burned more efficiently and produced less smoke because of its decreased density and viscosity. 8.2% less smoke was released under full load while using 10% DEE blend. At full load, 10% DEE blend enhanced BSEC and BTE and decreased CO and HC emissions [132]. Ahmad et al. (2023) found that, for all tested blends, BTE was less than that of diesel up to 3.3 kW. BTE greater with all blends except for 5% DBE (dibutyl ether) blend than diesel, which produced the best BTE above 30% at 4.24 kW. All tested blends exhibited reduction in NOx emission, with minimum value of 550 ppm. All blends exhibited reduction in HC emission, with a minimum value of 19.5 ppm. In comparison to diesel, 5% DEE blend increased BTE by 8.76% and decreased BSEC, BSFC, CO, and HC emissions by 8%, 2.6%, 15.7%, and 47.3% at 4.24 kW. Additionally, it resulted in notable drops in CO_2 and NOx emissions at all load [133]. According to Srihari et al. (2017), adding DEE to blend of 80% diesel–20% cotton seed oil biodiesel enhanced the density, cetane number, and auto ignition temperature. The maximum cylinder pressure was achieved with 3% DEE blend. Adding 3% DEE resulted in a significant decrease in emissions of HC, CO, and NOx. In comparison to the other blends, 3% DEE blend produced less smoke. DEE blends increased BTE and BSFC [134]. It was determined by Yesilyurt and Aydin (2020) that the rising DEE ratio in 20% diesel–80% cotton seed oil biodiesel blend increased ID and reduced the cylinder pressure and heat release rate. The rising DEE ratio also raised both BSFC and BSEC. 10% DEE blend reduced BTE by 17.39% while it raised BSFC by 29.15% compared to diesel. EGT of DEE blends was lower than diesel while it was higher than 20% biodiesel blend. DEE addition also reduced HC, smoke and NOx emissions up to 12.89, 4.12 and 8.84% compared to diesel. CO emission of 2.5% DEE and 5% DEE blends were lesser 31.86 and 32.29% than diesel while it was lower 21.79 and 22.47% than 20% biodiesel blend. CO_2 emission of diesel, 20% biodiesel, 2.5% DEE, 5% DEE, 7.5% DEE and 10% DEE blends were 400.97, 332.31, 282.44, 282.32, 336.84 and 380.63 g/kWh [135]. Karthick et al. (2014) found that BTE of all blends they tested increased as the load increased. The maximum BTE for blend containing 3% DEE at full load was 30.31%, which was 7.3% higher than diesel. When compression ratio (CR) was lowered, the emissions of smoke and NOx decreased. However, when diesel and jatropha oil biodiesel blends with DEE, the emissions of NOx increased and the emissions of smoke and NOx decreased. In terms of combustion, performance, and emissions, 3% DEE blend proved superior [136]. Satya et al. (2011) found that high injection pressure and a narrow nozzle hole enhanced engine performance and emissions. The addition of DEE to biodiesel blends containing 80% diesel and 20% jatropha oil biodiesel enhanced combustion and resulted in reduced emissions. 5% DEE blend reduced emissions of BSFC and HC; while 15% DEE blend resulted in lower NOx emissions. The addition of DEE to the diesel–biodiesel blend resulted in reduced smoke opacity [137]. It was determined by Abraham and Thomas (2015) that all tested fuel blends gave best performance at CR of 18. The peak cylinder pressure of 80% diesel–20% jatropha oil biodiesel blend was lower due to the decreasing delay period. BTE of 20% biodiesel blend was higher than diesel due to the better combustion and its better lubricity. BSFC of the biodiesel was higher due to its lower calorific value. 20% biodiesel blend gave the higher mechanical efficiency due to the improved spray quality, high reaction activity and decreased heat loss due to the lower flame temperature. The emissions of CO and HC were reduced and CO_2 emission was raised with DEE addition to the diesel–biodiesel blend due to the complete combustion. NOx emission was raised with 20% biodiesel blend due to its high oxygen content and combustion temperature, while it was reduced with 5% DEE blend due to low cylinder temperature [138]. Firew et al. (2016) found that while engine power for 20% DEE blend was lower than that of diesel, it was higher than that of 80% diesel–20% jatropha oil biodiesel blend, and the other blends. At higher loads, BSFC of 10% DEE blend was lower than that of the other blends at lower loads, it was lowest for 20% DEE blend [139]. Prasad et al. (2012) found that using small nozzle hole and high injection pressure resulted in better engine performance and lower emissions. The blend of 80% diesel–20% jatropha oil with 5% DEE produced superior performance and reduced emissions. 10% DEE and 40% biodiesel blend resulted in reduced BSFC. Emissions of NOx and HC were reduced when 5% ethanol was blended with 40% biodiesel. The diesel–biodiesel blends with DEE addition had reduced NOx emissions and smoke opacity [140]. It was determined by Imtenan et al. (2015) that n–butanol and DEE addition to diesel–jatropha oil biodiesel reduced the density and viscosity of the biodiesel blends. 20% blend gave the higher cylinder pressure than diesel due to the higher cetane number, but n–butanol and DEE addition reduced the cylinder pressure due to the retarded combustion and the higher latent heat vaporization of n–butanol and DEE additives. 20% biodiesel blend gave 5.4% higher BSFC than diesel, while 10% n–butanol blend reduced 3.9% BSFC than 20% blend and 10% DEE addition to 20% blend reduced 6.8% BSFC than 20% biodiesel blend. 20% biodiesel blend gave 8.2% higher NO emission than diesel while 10% n–butanol and 10% DEE addition to 20% biodiesel blend gave 8.8% and 12% lower NO emission. 20% biodiesel blend reduced 27.5% CO emission than diesel. 5 and 10% n–butanol addition reduced CO emission by 23 and 30.7% than 20% biodiesel blend due to the higher oxygen content while 5 and 10% DEE addition to the biodiesel blend reduced 11 and 20.6% CO emission. 20% biodiesel blend reduced smoke opacity by 6.2% than diesel. 10% n–butanol and 10% DEE addition to the biodiesel blend reduced smoke emission by 27% and 38.5% than 20% biodiesel blend. 20% biodiesel blend reduced HC emission by 28% than diesel, but n–butanol and DEE blends increased HC emissions [141]. Rao and Chary (2018) found that adding DEE to blend of 80% diesel–20% jatropha oil biodiesel decreased the density, viscosity, and flash/fire point, but improved its energy content. EGT increased with load, and adding 3% DEE to the biodiesel blend produced the lowest EGT. As the load increased, BTE also increased. Diesel–biodiesel blend with 3% DEE was gave the highest BTE at full load. At full load, the BSFC was 3.32% lower with 6% blend of DEE [142]. It was determined by Varpe et al. (2020) that DEE was fully miscible in diesel and biodiesel. DEE addition to diesel–jatropha oil biodiesel raised the volatility, cetane number, and viscosity, while it reduced the density and calorific value of the blends. The higher CR and loads enhanced BTE and reduced BSFC for all tested blends. 20% biodiesel blend with 10% DEE addition improved the engine performance and emissions compared to the other blends. BTE was raised by 21.14% and BSFC reduced by 15.84% with 10% DEE addition to the diesel–biodiesel blend compared to diesel. Smoke emission was reduced by 54.62% and HC emission was raised by 42.12% with 10% DEE blend compared to diesel. NOx emission was also raised with all tested blends [143]. Biradar et al. (2011) found that adding DEE caused the injection timing to be delayed, whereas using blend of 80% diesel–20% karanja oil biodiesel caused it to advance. When DEE was added to the biodiesel blend, the injection time increased, ID decreased, and the peak HRR increased. With 10% DEE blend, BTE increased by 6%. The inclusion of DEE did not significantly alter CO and HC emissions. NOx emissions of 10% DEE blend were close to those of diesel, which were 717 ppm for 20% biodiesel blend and 662 ppm for diesel [144]. It was determined by Manickam et al. (2014) that the peak cylinder pressure and heat release rate were raised and ID was reduced with 10% DEE and 15% DEE blends compared to 80% diesel–20% karanja oil biodiesel blend at full load. 10% DEE blend reduced BSFC by 8.6% while 20% DEE blend raised BTE by 4.8%. 10% DEE and 15% DEE blends reduced CO emission by 27% and 14% compared to pure biodiesel. HC emission was raised by 24% and 8% for 10% DEE blend and 15% DEE blend compared to 20% biodiesel blend at full load. NO emission was reduced by 27% and 32% for 10% DEE and 15% DEE blends compared to diesel at full load, while smoke emission was raised by 14% and 10% for 10% DEE and 15% DEE blends compared to 20% biodiesel blend at full load [145]. Tudu et al. (2015) found that growing DEE ratio decreased ID and increased the peak cylinder pressure. At full load, the engine performance and emissions of 60% diesel–40% light fraction pyrolysis oil biodiesel blend were superior to those of the other blends when 4% DEE was added. With 4% DEE blend, BSFC was 6% lower than diesel at full load. When using 4% DEE blend instead of diesel at full load, NO emissions were 25% lower. The inclusion of DEE also decreased smoke emissions [146]. Nagdeote and Deshmukh (2012) found that adding ethanol to diesel–mahua oil biodiesel blends decreased the BSFC, but it was similar with

DEE addition. While the blends of ethanol and DEE had lower CO emissions than the biodiesel, they had greater HC emissions. When DEE was added to the biodiesel blend instead of ethanol, the emission of smoke was lowered further, but NOx emissions increased [147]. It was determined by Mallikarjun et al. (2013) that NOx emission was reduced by rising EGR, but engine performance was unsteady due to insufficient oxygen and thus CO and HC emissions were raised to high levels. Mahua oil biodiesel with 30% EGR gave the lowest NOx emission at full load, but HC and CO emissions were high at this EGR ratio. The biodiesel with 20% EGR gave low HC and CO emissions besides the rising BTE close to diesel. NOx emission was less than diesel at this EGR ratio. The emissions of CO, HC and PM with the biodiesel were raised with retarding injection timing. But, these emissions were still lower than that of diesel. Injection timing of 20.9°BTDC (before top dead center) gave the optimum results. DEE addition to 80% diesel–20% mahua oil biodiesel blend reduced NOx and the other emissions and also improved the engine performance [148]. Sudhakar and Sivaprakasam (2014) found that adding DEE to 80% diesel–20% mahua oil biodiesel blend decreased the viscosity while increasing the atomization of the fuel–air mixture. With addition of DEE to the biodiesel blend, ID and NOx emissions were also decreased. Blends containing DEE increased BTE and smoke output. At maximum load, DEE blends also had greater CO and HC emissions [149]. Vadivel et al. (2015) found that adding DEE to diesel–mustard oil biodiesel enhanced the BTE and BSFC. In comparison to diesel at full load, the emissions of CO, HC, NOx, and smoke were reduced by 30%, 20%, 28%, and 19% for 75% diesel–25% biodiesel blend with 5% DEE [150]. Akshatha et al. (2013) found that adding DEE to diesel–neem oil biodiesel blend enhanced the density, viscosity, and flash point. Blends of biodiesel did not significantly alter engine performance; however, adding DEE to the blends improved the emissions. When the injection pressure was increased to 290 bars, BTE of biodiesel blends increased by 3.5%, but it was still lower than that of diesel at 250 bars. With increasing injection pressure, all tested biodiesel and DEE blends showed significant reductions in CO and HC emissions [151]. It was determined by Kumar and Rao (2014) that DEE addition to 80% diesel–20% neem oil biodiesel blend raised BTE, while it reduced BSFC and emissions of CO, HC, NOx, CO_2 and smoke [152]. Shrivastava and Sungra (2018) found that adding DEE to diesel increased the emissions of HC but decreased the emissions of CO, NOx, and smoke. DEE addition to diesel, however, had a detrimental impact on performance; that is, it increased BSFC and decreased BTE. Conversely, when DEE was added to 85% diesel–15% neem oil biodiesel and 70% diesel–30% neem oil biodiesel, BSFC was decreased and BTE increased. When DEE was added to the biodiesel blends, the emissions of CO, NOx, and smoke were likewise decreased, but emissions of HC were increased [153]. Ibrahim (2018) found that, in comparison to diesel, diesel–neem oil biodiesel blend increased the minimum BSFC and decreased the maximum BTE by 8.1% and 6.8%, respectively. While adding 10% DEE to the biodiesel blend decreased BTE, adding 5% DEE to the biodiesel blend significantly increased engine performance at most loads. The start of combustion was unaffected significantly by any of tested fuels or blends; however, with higher loads, diesel had a longer CD and lower HRR than the other fuels and blends. The engine operating stability was largely unaffected by the addition of DEE to the biodiesel blend [154]. Ali et al. (2016) found that 80% diesel–20% nerium oil biodiesel decreased BTE. However, 80% diesel–20% nerium oil biodiesel blend with 15% DEE had closer BTE values to diesel. But, BSEC for 15% DEE blend was the same as diesel, but it was higher for 20% biodiesel blend. With the addition of DEE to the biodiesel blend, ID was shortened and HRR and peak cylinder pressure were decreased. With the addition of DEE to the biodiesel blend, emissions of NOx and smoke were reduced, while emissions of CO and HC increased [155]. It was determined by Annamalai et al. (2014) that the minimum pour point was –7°C for 6% DEE addition to diesel–palm oil biodiesel blend while it was 14°C for biodiesel. 6% DEE blend also reduced the viscosity, density, acid value, and heating value by 35%, 3.6%, 57% and 1% compared to biodiesel [156]. Ali et al. (2016) found that adding 8% DEE to 70% diesel–30% palm oil biodiesel blend decreased the viscosity, heating value, pour/cloud point, and temperature by 26.5%, 4%, 4°C, and 3°C in addition to lowering the density and acid value. The blend with 30% biodiesel had the lowest coefficient of variation (COV), and it increased as the DEE ratio increased [157]. Imtenan et al. (2014) found that adding DEE to diesel–palm oil biodiesel blends increased the brake power by 6.25%, reduced BSFC by 3.28%, and increased BTE by 4% when compared to 80% diesel–20% palm oil biodiesel blend. In addition to lowering NO and CO emissions, adding DEE to the biodiesel blend also increased HC emissions [158]. Imtenan et al. (2015) found that adding DEE to diesel–palm oil biodiesel blend decreased advanced combustion by increasing ID and decreased cylinder pressure and temperature because of the increased latent heat of evaporation. In comparison to 80% diesel–20% palm oil biodiesel blend with inclusion of DEE decreased CO and smoke emissions by 25% and 35.5%, respectively. When 10% DEE was added to the biodiesel blend, NO emission was similarly reduced by 20%; however, HC emission increased with DEE blends [159]. It was determined by Varaprasad and Rao (2017) that the lower DEE addition to diesel–palm oil biodiesel blends improved the more BTE. DEE addition to the biodiesel blends reduced the emissions as well. Hence, DEE could be used as a prospective additive in diesel engines [160]. Prasadarao et al. (2014) found that adding DEE to diesel–palm oil biodiesel blend increased BTE by 10.8% in addition to reducing BSFC, CO, NOx, and CO_2 emissions. The optimal blend for increasing performance and emissions was suggested to be 85% diesel, 15% biodiesel, and 5% DEE addition [161]. It was determined by Uslu (2020) that the best working parameters were determined as 5% DEE ratio, 6%

biodiesel ratio and 850 W loads. The best values of BTE, BSFC, NOx and smoke emissions were obtained as 30.73%, 824.59 g/kWh, 292.2 ppm and 68.91% for the optimum working parameters [162]. It was determined by Uslu and Aydın (2020) that the high biodiesel ratio in the diesel–palm oil biodiesel blend reduced CO and smoke emissions, but low biodiesel ratio raised BTE, reduced BSFC and the emissions of HC and NOx. Low DEE ratio in the diesel–palm oil biodiesel blend raised BTE, while it reduced BSFC and CO emission. High DEE ratio reduced NOx and smoke emissions. Middle DEE ratio gave the ideal EGT and HC emission. Early injection reduced the emissions of CO, HC and NOx, while the retarding injection improved EGT, BTE and smoke. The best BSFC was obtained at average injection timing. The best EGT and the emissions of HC and NOx were achieved at low load, while the best BTE, BSFC and CO emission was obtained at middle load. The high load gave the optimum values for only smoke emission [163]. It was determined by Hardiyanto and Prawoto (2023) that DEE addition to 65% diesel–35% palm oil biodiesel blend raised the engine power and BTE and reduced BSFC and the emissions compared to the 35% biodiesel blend. 4% DEE addition to the biodiesel blend raised BTE by 7.69% and reduced BSFC by 6.3% compared to BD35. DEE3 reduced CO by 1.82% compared to BD35 while it reduced by 8.25% compared to diesel. NOx emission for DEE4 was lower 53.48% than BD35 and it was less 48.88% than diesel. SO_2 for DEE4 was less 40.89% than BD35 and it was lower 71.17% than diesel [164]. Gurusamy and Subramanian (2023) found that benzyl alcohol and DEE premixing increased BTE by 4.5% and 8.75% in comparison to 50% diesel–50% pine oil biodiesel blend, but BSFC of biodiesel blend was lower. While NOx and smoke emissions were decreased, CO and HC emissions were increased when DEE and benzyl alcohol were premixed. When benzyl alcohol was premixed, the peak cylinder pressure and HRR increased; however, when DEE was premixed, they decreased [165]. Samuel et al. (2016) found that BTE was lower in all studied blends when compared to diesel, and that adding 15% DEE to the diesel–pongamia oil biodiesel blend resulted in BTE values that were closer to diesel. Diesel fuel produced the lowest BSFC values, and all tested blends raised BSFC at all loads. The biodiesel blend's addition of DEE decreased EGT as well as CO, NOx, and CO_2 emissions [166]. It was determined by Pugazhvadivu and Rajagopan (2009) that DEE addition to diesel–pongamia oil biodiesel blends reduced BTE and the emissions of NOx and smoke. 15% and 20% DEE blends was more beneficial for the reducing of NOx than 10% DEE blend [167]. Danesha and Manjunath (2016) found that at partial loads, 80% diesel–20% simarouba glauca seed oil biodiesel blend and 80% diesel–19% biodiesel with 1% DEE addition produced greater BTE than diesel. The addition of 0.5% and 1% DEE to the biodiesel blend produced nearly identical BSFC with diesel. At greater loads, the NOx emission for every tested blend was lower than that of diesel. All investigated blends had lower HC and CO emissions but higher CO_2 emissions [168]. Prabu et al. (2020) found that 90% diesel–10% soapnut oil biodiesel with 5% DEE had lower cylinder pressure and HRR than diesel, which resulted in smooth engine performance. 10% biodiesel and 5% DEE blend produced nearly identical BSFC with diesel. BTE was raised by 2.9% and NOx emission was reduced by 32.1% when DEE was added to biodiesel blend. However, adding DEE to the biodeiesel blend increased the emissions of CO and HC. It was determined that 10% biodiesel blend with 5% DEE was a good diesel replacement [169]. Muneeswaran and Thansekhar (2015) found that adding DEE to diesel–soybean oil biodiesel blends decreased ID, which in turn decreased the combustion temperature. When DEE was added to the biodiesel blends, the emissions of CO and NOx were decreased while the emissions of HC were increased. It was declared that reducing NOx emissions may be achieved by blending 70% diesel–30% biodiesel with DEE [170]. Navaneethakrishnan and Vasudevan (2015) found that adding DEE to 60% diesel–40% tamanu oil biodiesel increased BTE to 3.4 percent and BSFC to about the same as diesel. Adding DEE to the biodiesel blend decreased the cylinder pressure and all emissions, with the exception of NOx [171]. Raju et al. (2017) found that 80% diesel–20% tamarind seed oil biodiesel blend with 10% DEE increased BTE by 7.7% and decreased BSFC by 5.36% in comparison to diesel. The addition of DEE to the biodiesel blend increased NOx emissions while reducing CO, HC, and smoke emissions. At full load, the biodiesel blend with 10% DEE produced 43.85% less smoke than diesel. It was determined that blends containing 10% DEE and 20% biodiesel performed better and produced lower emissions than the other blends [172]. It was determined by Raju et al. (2020) that 12% addition to 80% diesel–20% tamarind seed oil biodiesel (BD20) blend raised the heat release rate and BTE by 8.88% and 4.22% compared to the 20% biodiesel. The emission of CO, HC, NOx and smoke for this blend were reduced by 10.68%, 33.33%, 10.33% and 27.72% compared to diesel at full load. It was declared that BD20 blend with 12% DEE was hopeful both experimentally and theoretically [173]. Tudu et al. (2016) and Murugan et al. (2017) found that increasing DEE ratio in 60% diesel–40% tyre derived pyrolysis oil biodiesel (BD40) decreased ID and increased cylinder pressure. When 4% DEE was added to the biodiesel blend, BSFC was 6% lower than that of diesel at full load. At maximum load, NO emission for this blend was 20% greater than that of BD40 and 25% lower than that of diesel. At full load, smoke emission of 3% and 4% DEE were 26% and 21% less than those of diesel and 39% and 34% less than those of BD40. Moreover, these DEE blends decreased CO emission [174–175]. It was determined by Padmanabhan et al. (2023) that BTE of 80% diesel–20% waste cooking oil biodiesel blend (BD20) with 20% DEE was higher 5.2% and BSFC was lower 15% than that of diesel. DEE blends also reduced the emissions of CO, HC and NOx emissions about 7–9%, 9% and 4.2–13.4%, respectively [176]. Krishnamoorthi and Natarajan (2015) found that when DEE mixes were used instead of diesel, BSFC and emissions were reduced. The lowest emissions of HC, CO, NOx, and CO_2 were produced by 75% diesel–25% waste frying oil biodiesel (BD25) blend with 5% DEE [177]. It was determined by Dubey et al. (2023) that 65% diesel–35% waste soybean cooking oil biodiesel (BD35) blend with 10% DEE and 15% EGR was determined as an optimal. BSFC, BTE and the emissions of smoke, NOx, CO, and HC were obtained as 272 g/kWh, 31.47%, 18.94 HSU (Hartridge Smoke Unit), 91 ppm, 0.03% and 24 ppm at these optimal conditions [178]. Reddy et al. (2022) found that 80% diesel–20% waste plastic oil biodiesel (BD20) with 10% DEE increased BTE by 4.86% while improving cylinder pressure and HRR. Compared to diesel, BD20 blend with 10% DEE had emissions of CO, HC, and smoke that were reduced by 52%, 20.73%, and 15.49%, respectively [179]. Kotturi et al. (2023) found that adding DEE to 80% diesel–20% waste plastic oil biodiesel (BD20) decreased viscosity, which enhanced fuel mixture atomization and combustion efficiency. In comparison to BD20 and the other DEE blends, BD20 blend with 15% DEE produced better BTE. At high engine speeds, BSFC of DEE blends was more similar to diesel. The peak cylinder pressure and HRR were lowered by adding DEE to the BD20 blend. Additionally, it decreased CO and NOx emissions, but increased HC emissions [180]. More et al. (2020) found that 0.8% DEE addition to 80% diesel–20% used cooking oil biodiesel (BD20) blend increased BTE by 16.06% and decreased BSFC by 4.12%. In comparison to diesel, DEE blends decreased CO, HC, and NOx emissions by 20.41%, 34.69%, and 23.33%, respectively. Blends of DEE also decreased CO_2 emissions [181]. Senthil et al. (2015) found that adding 10% DEE to 80% eucalyptus oil–20% pongamia oil biodiesel (BD20) produced BTE values that were closer to those of diesel and significantly reduced BSEC, BSFC, and EGT at full load. Additionally, CO, HC, and smoke emissions of this blend were 30%, 10%, and 35.7% less than diesel at full load [182]. It was determined by Qi et al. (2011) that 5% DEE addition to 70% diesel–30% biodiesel (BD30) blend reduced BSFC compared to BD30 blend, while it was similar to that of BD30 blend for ethanol addition to BD30 blend. Ethanol or DEE addition to BD25 blend reduced smoke emission at higher loads. Ethanol blend raised the emissions of HC and NOx while DEE blend raised HC emission, but CO emission was lower for both ethanol and DEE blends. The peak cylinder pressure, pressure rise rate and heat release rate for DEE blend were similar to BD30 and higher than those of ethanol blend at low loads. The peak cylinder pressure, pressure rise rate and heat release rate for DEE blend were highest while they were lowest for BD30 blend at high loads. It was declared that DEE blend was better than those of ethanol and BD30 blends [183]. Roy et al. (2016) found that while CO and NOx emissions decreased, HC emissions increased following warm–up as opposed to cold start. Diesel–canola oil biodiesel blends increased NO emission relative to diesel, but they decreased CO and HC emissions. While the addition of DEE to diesel–biodiesel blend increased the emissions of HC, the addition of ethanol and DEE to the blends decreased the emissions of CO and NOx. There was no discernible increase in aldehyde emissions, and no blends produced any smoke after the warm–up period [184]. Carvalho et al. (2020) found that adding 10% ethanol to 80% diesel–20% biodiesel (BD20) blend decreased the maximum torque by 7.8% and 6.7% when compared to the diesel and BD20 blend. When ethanol was added to BD20 at low loads, CO and HC emissions increased in comparison to diesel and BD20 blend. The maximum engine torque was not significantly altered by adding 5% DEE to the diesel, biodiesel, and ethanol blend. At moderate and high loads, the addition of DEE reduced NOx and PM emissions by 71% when compared to diesel and BD20. Every tested blend of BTE was fairly close to each other, although the DEE blend produced the highest BTE at high loads [185]. It was determined by Venu and Madhavan (2017) that DEE addition to diesel–biodiesel–ethanol blend raised the peak heat release rate, BSFC and the emissions of HC, CO and CO_2 besides the reduction in peak pressure and the emissions of NOx and smoke. Alumina (Al_2O_3) addition to diesel–biodiesel–ethanol blend raised the emissions of NOx and smoke besides the reduction in the peak heat release rate, BSFC and the emissions of HC, CO and CO_2. Addition both Al_2O_3 and DEE resulted in higher particulate matter (PM) formation, but 5% DEE and 25 ppm Al_2O_3 addition reduced PM at higher loads. It was declared that 5% DEE and 25 ppm Al_2O_3 gave the better performance and emission characteristics [186]. It was determined by Venu and Madhavan (2017) that DEE addition to ethanol–biodiesel–diesel blend raised the combustion duration, cylinder pressure and BSFC with the reduced NOx, PM and smoke emissions. DEE addition to methanol–biodiesel–diesel blend raised PM, CO, CO_2 and smoke emissions with reduced combustion duration, cylinder pressure, heat release rate and BSFC. 5% DEE addition gave the higher cylinder pressure, heat release rate, EGT and NOx emission with reduced combustion duration and the emissions of HC, CO_2 and PM compared to 10% DEE addition. It was declared that 5% DEE addition to ethanol/methanol–biodiesel–diesel blends gave the better combustion, performance and emissions [187]. It was determined by Sathiyamoorthi et al. (2017) that DEE addition to nano emulsified 75% diesel–25% lemongrass oil biodiesel (BD25) blend with EGR reduced the emissions of NOx and smoke by 30.72% and 11.21% compared to BD25 blend. BTE and BSFC were raised by 2.4% and 10.8%, but the emissions of HC and CO were reduced by 18.18% and 33.31% for this fuel combination compared to BD25 blend. The cylinder pressure and heat release rate raised by 4.46% and 3.29% and ignition delay and combustion duration raised for this fuel combination compared to BD25 blend [188]. It was determined by Vellaiyan et al. (2023) that the optimum ratios for biodiesel, water and DEE were determined as 15.23%, 15% and 15%. BSFC, BTE, CO, HC, NOx and smoke values were obtained as 243.729g/kWh, 28.2358%, 31.0326ppm, 0.09248%, 717.542 ppm and 17.5861% at this optimum blending ratios [189]. The effects of DEE on the fuel properties, injection, combustion, performance and emissions characteristics were also reviewed in details by Sezer (2018, 2019, 2020) [190–196].

5. Effects of Diethyl Ether on Cyclic Variations

The coefficient of variation (COV) of the indicated mean effective pressure (IMEP) is used to assess the stability of engine. The cycle to cycle variations are observed when cylinder pressure is measured over multiple thermodynamic cycles without interruption. The cycle to cycle pressure variation is mainly a result of variations in the combustion process from cycle to cycle [197]. The COV of IMEP is a significant indicator of the cyclic variability that may be computed from recorded cylinder pressure data. It is computed as follows [198, 199]:

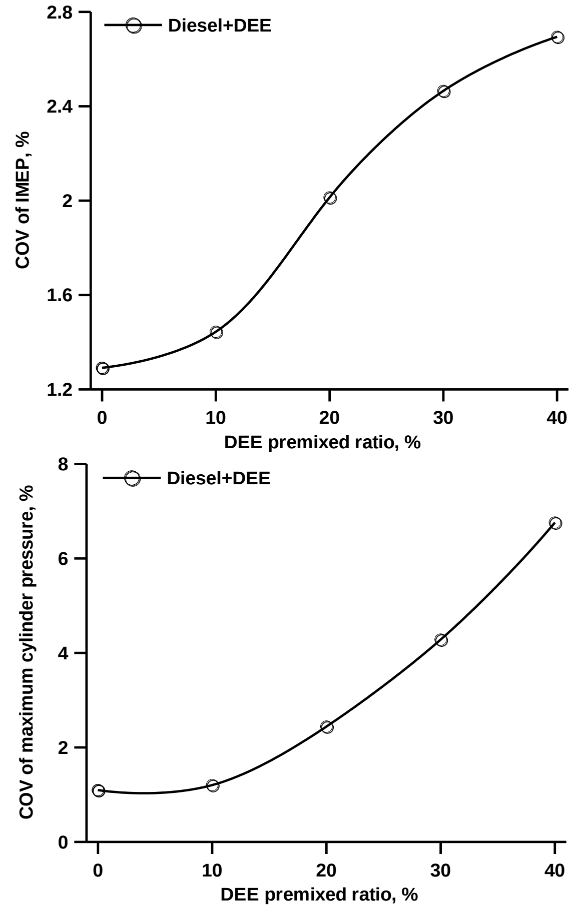
$$COV = \frac{\sigma_{IMEP}}{\overline{IMEP}} x100 \tag{1}$$

Where, $\overline{IMEP}$ is the average indicated mean effective pressure calculated for a number of cycles N, while σ_{IMEP} is the standard deviation in IMEP. These parameters are calculated as follow [198, 198]:

$$\overline{IMEP} = \sum_{i=1}^{i=N} IMEP(i)/N \tag{2}$$

$$\sigma_{IMEP} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{i=N}\left(IMEP(i) - \overline{IMEP}\right)^2} \tag{3}$$

Heywood [197] declared that engine stability was negatively impacted when COV exceeded 10%. However, other studies declared that engine stability started to deteriorate when COV increased beyond 5% [199].

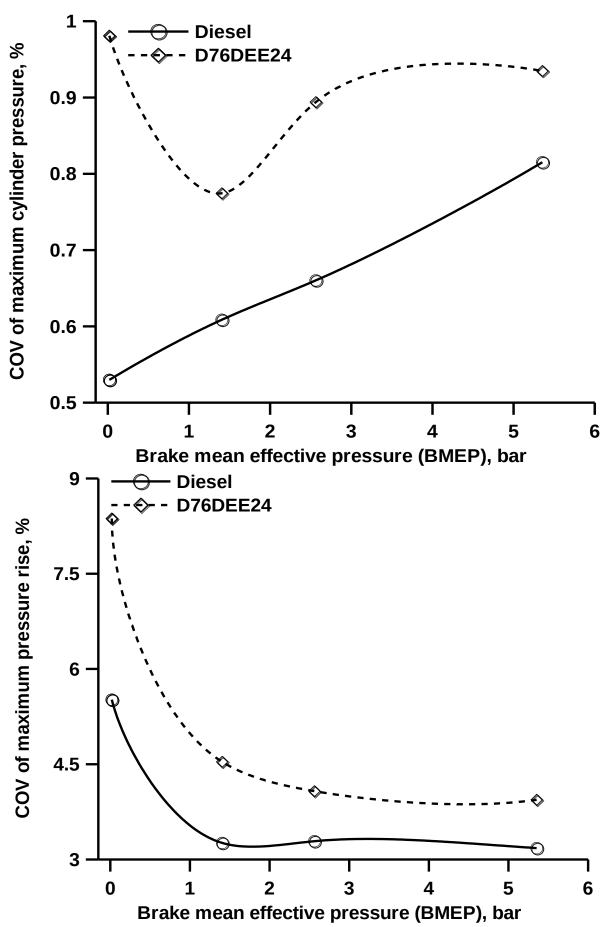


(a)

(b)

Figure 3. *Variation of a) COV of IMEP and b) COV of maximum cylinder pressure (p_{max}) with DEE premixed ratio [31]*

The effects of the DEE premixed ratio on the cyclic variation of 50 consecutive cycles are displayed in Figures 3(a) and (b). The cyclic variation usually affected by knocking and combustion instability when considering the operating limits of engine. It is declared that DEE premixed ratio was limited to 40%, since audible knocking was observed during the tests. The cyclic variations for diesel fuel and 10% DEE premixed ratio were quite small as seen from Figures 3(a) and (b). The cyclic variations started to come into sight at 20% DEE premixed ratio. The difference in the maximum cylinder pressures of each cycle increased continuously as DEE premixed ratio was raised. The values of COV of IMEP shown in Figure 3(a) were determined as 1.29, 1.44 and 2.01 for diesel, 10% and 20% DEE premixed ratios, respectively. The COV of P_{max} shown in Figure 3(b) was also determined as 1.08, 1.2 and 2.44 for diesel, 10% and 20% DEE premixed ratios, respectively. During the high premixed DEE ratio, rapid combustion of the bulk premixed fuel occurred, leading to excessive heat release rate which caused unstable ignition timing. The knocking combustion is clearly observed from pressure oscillations especially during 30% and 40% DEE premixed ratio. The cyclic variation was excessive with 40% DEE premixed ratio, with the fluctuation of the maximum cylinder pressure, ignition timing and crank angle related to the highest cylinder pressure. The COV of IMEP was 2.4 and 2.6 while the COV of p_{max} was 4.2 and 6.7 at 30% and 40% DEE premixed ratios. The higher premixed fuel ratio can lead to fuel film formation on the intake manifold walls and the head of the intake valve in external homogeneous charge formation with port type fuel injection. Hence, the trapped homogeneous charge in the cylinder at the intake valve closure can show variations from cycle to cycle. The rising intake charge temperature leads to the increased vaporization of premixed fuels and decreased formation of fuel films on the intake manifold wall. It can be concluded that controlling the intake charge temperature during the homogeneous charge formation can provide stable engine operation. It can reduce the ignition delay caused from intake charge cooling. The combustion temperature can be also increased by heating the intake charge. It can reduce the ignition delay caused from intake charge cooling and promotes the chemical reaction rate. In consequence, stable ignition and engine running can be achieved. The application of EGR can reduce cylinder pressure rise rate for higher premixed DEE ratio. Hence, it can be used for the engine knocking controlling [31].



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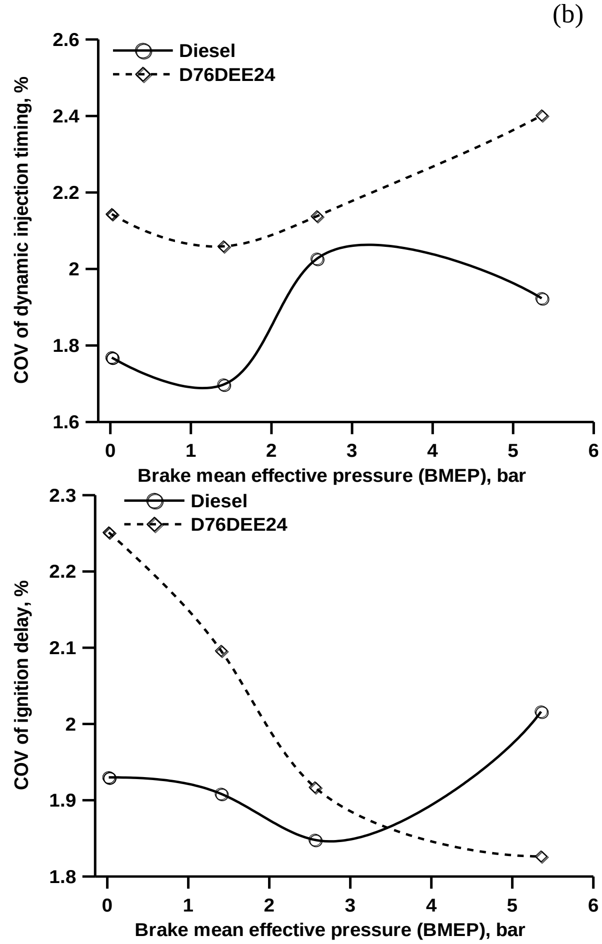


(c)

(d)

Figure 4. *Variation the COV of a) maximum cylinder pressure, b) maximum pressure rise, c) dynamic injection timing and d) ignition delay with BMEP for diesel–DEE blend [74]*

Figure 4(a) and (b) demonstrate the COV of the maximum cylinder pressure and maximum pressure rise with brake mean effective pressure (BMEP) for pure diesel and the blend of 24% DEE with diesel fuel (D76DEE24), respectively. Figure 4(c) and (d) indicate the COV of dynamic injection timing and ignition delay, respectively. From Figure 4(a)–(d), it could be concluded that the addition of DEE up to 24% blending ratio did not significantly change cyclic variability when compared to diesel fuel, which was already small. It was declared that the analysis of the results from the figures show that neither the injection process nor the DEE ratio in diesel–DEE blend had any adverse effect on the observed cyclic variations. It was assessed from the results that the engine would not have an unstable operation for up to a 24% DEE addition [74].

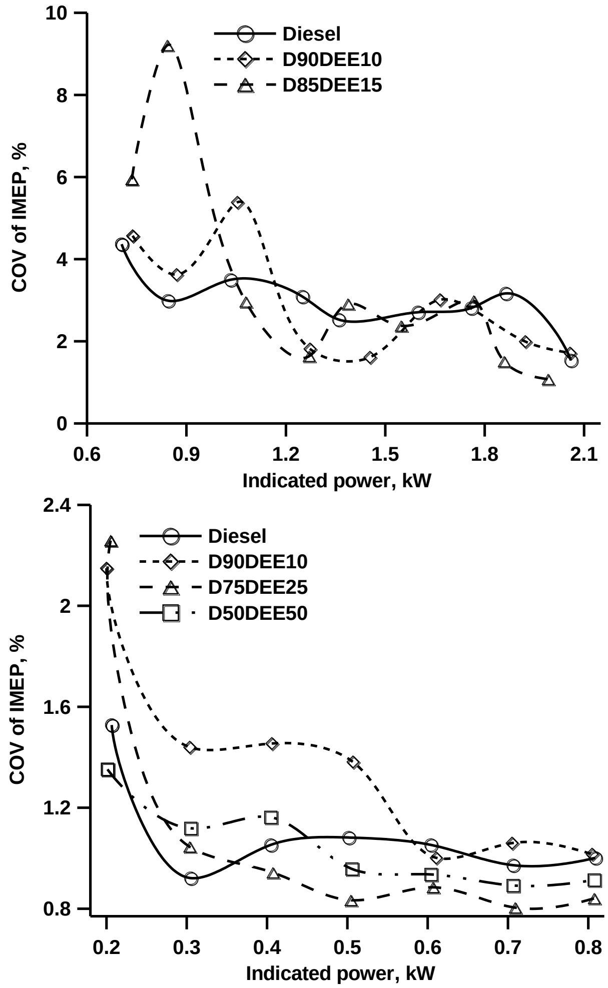


Figure. 5. *Variation the COV of IMEP for diesel fuel and various diesel–DEE blends with indicated power a) [26] and b) [24]*

Figure 5(a) shows COV of IMEP by the indicated power for tested fuels. It was stated that values of COV of IMEP were computed for five thermodynamic cycles. As seen from Figure 5(a), the values of COV are usually higher at the lower engine loads compared to higher loads especially for D85DEE15 blend. It was stated that this was because the engine was operated with the leaner fuel–air mixture during lower load operation and the operating of the engine with leaner fuel–air mixtures can raise the engine cyclic variations. It was determined that COV of IMEP values are below 5% for the most of engine loads especially at higher engine loads for all tested fuels. However, average COV of IMEP values raised slightly when DEE blends were used compared to diesel fuel. It was determined that average COV of IMEP for diesel, D90DEE10 and D85DEE15 was 2.85%, 2.98%, and 3.391%, respectively. It was stated that rising DEE ratio increased the amount of the fuel vapor bubbles due to high volatility of DEE causing vapor lock, which decreased engine stability and increased COV of IMEP [26]. Figure 5(b) indicates the COV of IMEP averaged over 200 engine cycles. Commonly, 5% COV of IMEP value is considered a cutoff that determines combustion stability. The COV of IMEP values were comparable and were less than 2.5% for all tested fuels under all engine loads, which pointed out very much stable combustion. As the engine load increased, the combustion stability also raised, showing the lower COV of IMEP values. This was because the quantity of injected fuel increased by rising engine load, which assisted the formation of the local fuel–rich region in the combustion chamber [24].

Figure 6 shows the COV of IMEP values for diesel, biodiesel (BD), and biodiesel–DEE blends including up to 40% DEE. The COV of IMEP values are about two/three times higher for DEE30 and DEE40 blends than that of diesel fuel. The results demonstrated that the combustion process of the biodiesel blend containing large amounts of DEE was more unstable. Such an engine operation presented the appropriate torque, but its uniformity of operation was also worse than that of diesel fuel. It was stated that the reason for higher variability of combustion process of biodiesel–DEE blends was sourced from disturbance of the fuel injection process. It was determined that the average value of IMEP was 0.648 bar for the cycle no of 70 while it is 0.731 bar for the cycle no of 71 when the engine was operated under 100 Nm and 1200 rpm operating conditions when engine fuelled with DEE40 blend. It was stated that lower IMEP was caused by a disorder in the fuel injection process. It was assumed that cause of failure in the fuel injector work was vapor lock formed in the fuel system caused by the evaporation of volatile DEE and it was also the reason for the difficult start–up of the engine fueled with biodiesel and large DEE ratio. The analysis of the results revealed that the variation in the combustion process depended on the variability of diesel fuel, biodiesel fuel, and biodiesel–DEE blends including up to 20% DEE ratio. In these cases, COV of IMEP did not exceed 4%. Moreover, it became obvious that COV of IMEP was raised with the higher DEE ratio in the biodiesel–DEE blends. Thus, the values of COV of IMEP for 30 and 40% of DEE with biodiesel were three times higher than those of diesel fuel. The results indicated that raised DEE into biodiesel is disadvantageous as it leaded to excessive roughness in engine operation compared to diesel fuel. The observed deterioration of the combustion process is caused by vapor locks, which were formed due to evaporation of volatile DEE in the fuel line, leading to the interrupted operation of fuel injector [97].

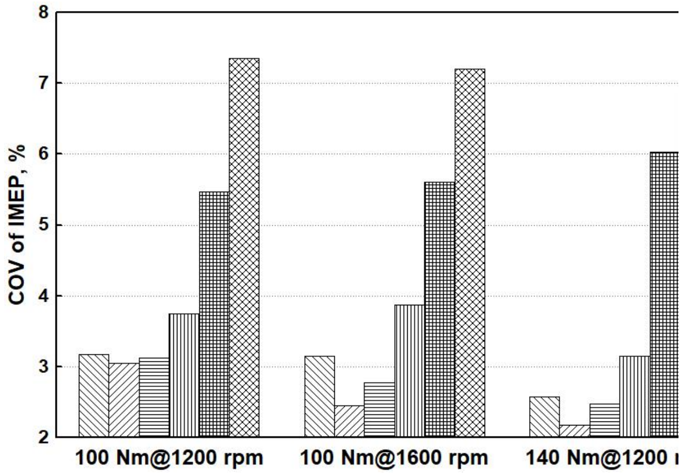


Figure 6. *Variation the COV of IMEP for diesel, biodiesel and biodiesel–DEE blends [97]*

Figure 7(a) shows the comparison of COV of IMEP determined from over a 200 consecutive cycles for all tested fuels. It is seen from Figure 7(a) that the variation in COV of IMEP was reduced by the rising number of cycles. This tendency indicated that the increase in the number of cycles was reduced the effects of cyclic variability in the averaged IMEP pressure data. Moreover, COV of IMEP tends to be constant with less than 1% error when the cycle number is more than 150 for all tested fuels. Therefore, 200 cycles was assumed sufficient to examine the engine cyclic variations. Figure 7(b) shows the effect of rising DEE ratio on COV of IMEP for BD30 blend. As seen from Figure 7(b) that COV of IMEP was lower for BD30 blend without DEE additive and increases with rising DEE ratio. This observation was due to effect of different chemical compositions, low flash point and high volatility of DEE on combustion process of the mixture which leaded to developed more engine cyclic variations [154]. Figure 7(c) indicates the variation of COV of IMEP with load for tall tested fuels. As seen from Figure 7(c) that COV of IMEP was lower than 5% for most of engine operating conditions. Therefore, it could be stated that adding DEE up to 10% into diesel–biodiesel blend did not negatively affect engine stability. Figure 7(c) also indicates that COV of IMEP generally reduced with the rising of load showing better engine stability. That could be explained as the engine consumed the richer air–fuel mixture at higher loads. The reducing the air–fuel ratio could decrease engine cyclic variations. The COV of IMEP for diesel fuel was determined about 3% for most of engine loads as seen in Figure 7(c). That could be considered slightly higher compared to other diesel engines because the air flow rate was measured using an orifice meter which was the flow restriction device which could induce relatively higher fluctuations in inlet pressure and air flow rate. However, COV of IMEP could change much from engine to engine according to engine specifications, operating conditions and fuel properties [152].

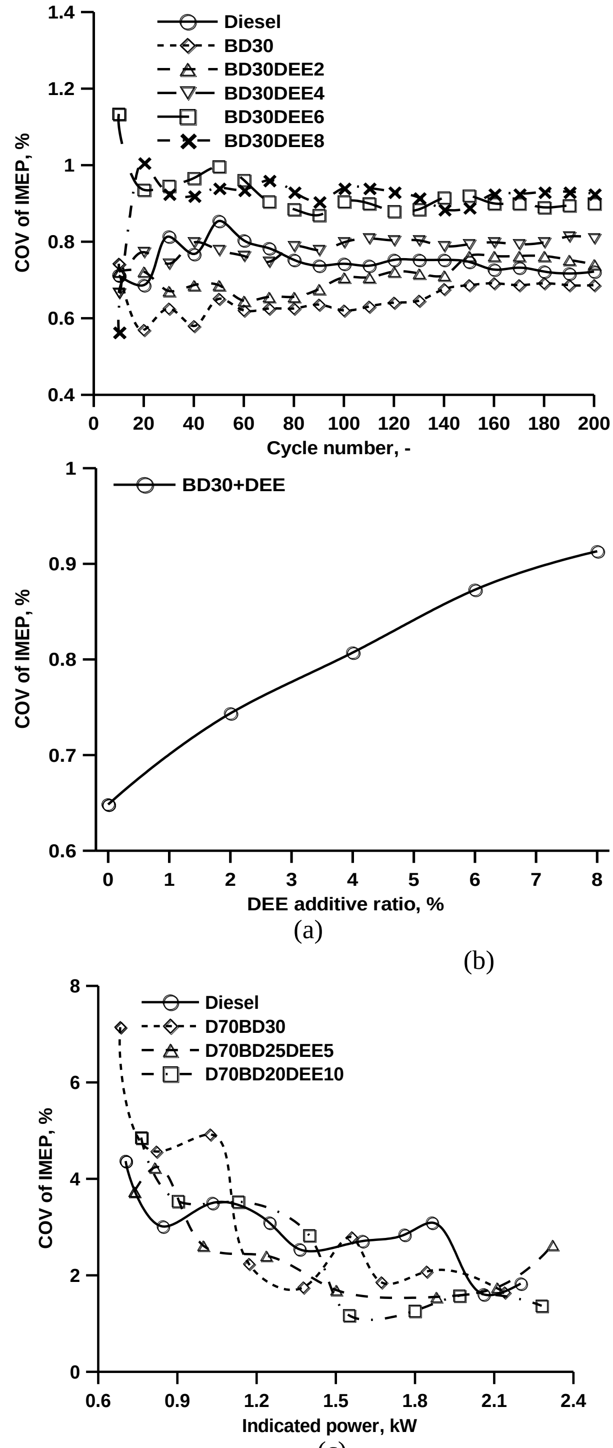
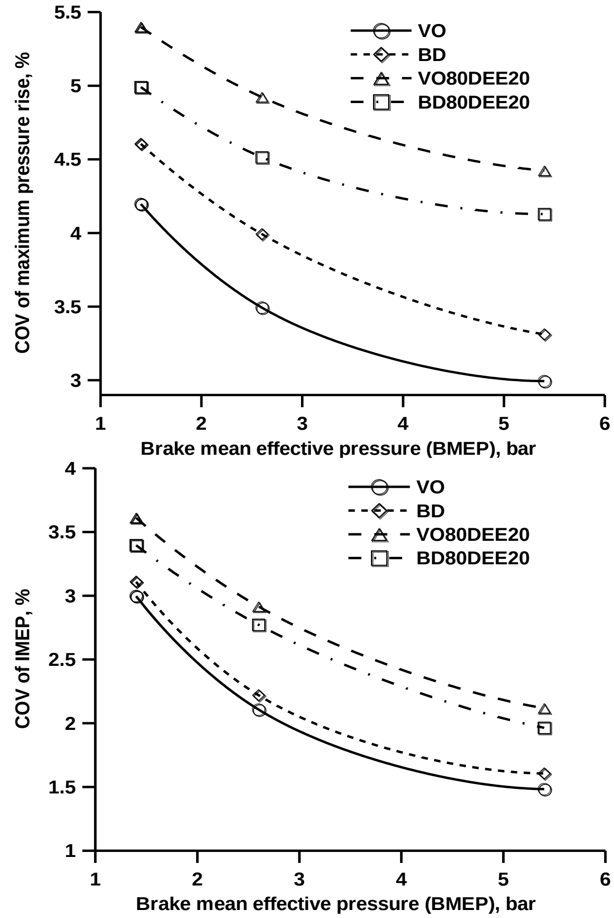


Figure 7. *Variation the COV of IMEP for diesel–biodiesel–DEE blends with a) cycle number, b) DEE ratio [154] and c) indicated power [152]*

Figure 8(a) shows the COV of maximum cylinder pressure rise with load (BMEP) for vegetable oil (VO), biodiesel (BD) and their blends with 20% diethyl ether. Firstly, it was observed that COV values of maximum cylinder pressure rise with pure VO or its blend with biodiesel were lower than the values for DEE blends. All COV values were raised with load because the more fuel is injected and combusted. The lower COV values at high load were possibly due to the fuel mixture reaching then over–richness at the point where the maximum rate occurred. As regards the corresponding COV values, it could be observed that there were slight differences between the neat VO and its blend with biodiesel and little higher values with their blends with DEE, but inside acceptable limits for this parameter in diesel engines. The little higher values observed for DEE blends with either VO or its blend with biodiesel indicated that this might be due to their corresponding higher ignition delays, which may have the dominant factor for less repeatable first (premixed) part of combustion to occur as against a less delayed combustion. However, COV values among these blends did not seem to correlate with the ignition delays. To be noted that all COV values were reduced with load, given that in the case of lower loads, having also higher ignition delays, the smaller amount of fuel injected (less controllable) and the consequent combustion process were less repeatable. Figure 8(b) shows the COV of IMEP values with load for VO, BD, and their blends with 20% diethyl ether. The related COV values, it could be observed that there were slight differences between the neat VO and its blend with biodiesel, and little higher ones by their blends with DEE, but inside acceptable limits for diesel engines. The higher COV values observed with all blends against the neat bio–fuel cases indicate that this might be due to their corresponding higher ignition delays having the dominant factor. On the other hand, it was observed that there were no apparent differences at all DEE blends with either VO or its blend with biodiesel. This indicated that when all DEE blends were compared, the differences in their ignition delays were not evident, likely being compensated for by other factors that were integrated into the computation of the cylinder pressure diagram for IMEP. All COV of IMEP values were reduced with the rising engine load similar to Figure 8 (a) [80].

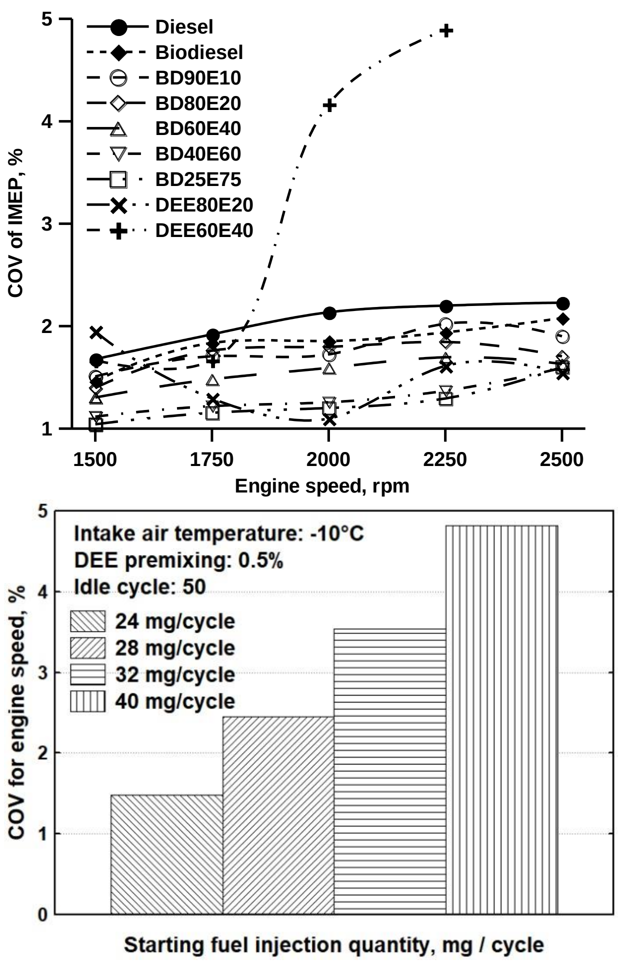


(a)

(b)

Figure 8. *Variation of a) COV of IMEP and b) COV of maximum pressure rise for vegetable oil (VO), biodiesel (BD), VO–BD blend with DEE [80]*

Figure 9(a) shows the variation of COV of IMEP with engine speed for diesel, biodiesel, biodiesel–ethanol blends and ethanol–DEE blends. The engine stability was highly affected with B20E80, exceeding limits that would allow vehicle drivability. Hence, BD20E80 did not show in Figure 9(a). DEE80E20 presented the same cyclic variability like the other blends, but not following the same trend as presented in Figure 9(a). However, DEE60E40 showed much higher COV of IMEP values than other fuels and blends after engine speed of 1750 rpm and engine operation were interrupted at engine speed of 2250 rpm as in Figure 9(a). On the other hand, COV of IMEP values would be different as the fuel pump injection timing should be optimized for each blend. Nevertheless, the addition of ethanol into biodiesel appeared to benefit combustion stability due to lowers values of COV of IMEP. The more ethanol in biodiesel gave the more stable combustion. The increasing amount of DEE also improved combustion stability, but in a narrow range. Less than 60% DEE with ethanol did not allow engine operation while 80% DEE with ethanol (DEE80E20) gave good combustion stability [70]. Figure 9(b) shows the starting fuel injection quantity (SFIQ) effect on the COV of engine speed during the initial 50 idle cycles at –10°C. Evidently, as the SFIQ decreased, COV of engine speed exhibited a corresponding reduction. It indicated that when 0.5% DEE was premixed, cutting down the fuel injection quantity enhanced the stability of engine speed during the cold start. This effect resulted primarily from the fact that a smaller fuel quantity led to a narrower gap between the maximum engine speed and the targeted idle speed, enabling the PID controller too quickly and precisely regulate fuel injection during the idle period. As seen in Figure 9(b), using a smaller SFIQ was beneficial for increasing the safety and stability of combustion during cold start of the diesel engine with 0.5% DEE premixed, but speed–up period was extended [42].



(a)

(b)

Figure 9. *Variation of a) COV of IMEP with engine speed for ethanol and DEE blends [70] and b) COV for engine speed with the starting fuel injection quantity (SFIQ) [42]*

6. Conclusions

The effect of diethyl ether (DEE) addition to various diesel engine fuels or fuel blends is investigated on the cyclic variations in this review study. The following conclusions can be summarized as results of the study.

- It was declared that coefficient of variation (COV) was usually higher for the low engine loads compared to the high loads due to engine was operated with the leaner fuel–air mixture. Operating of engine with leaner mixtures could increase cyclic variations by deteriorating combustion, while increasing quantity of injected fuel by rising engine load reduced cyclic variability due to enhancing combustion stability.
- It was determined that COV values raised a little with DEE addition to diesel fuel up to 24% DEE ratio, but it did not impact greatly the cyclic variability. COV values stayed under 2.5% for diesel–DEE blends up to 50% DEE ratio. COV values were determined as 2.85%, 2.98% and 3.391%, respectively for diesel, 10% DEE, and %15 DEE with diesel.
- It was declared that cyclic variations were often affected from knocking combustion which is also determined the engine operation limits. It was also declared that cyclic variations began to view at 20% DEE premixed ratio with diesel and knocking combustion could be noticed at 30% and 40% DEE premixed ratios. It was determined that COV of IMEP was 1.29%, 1.44%, 2.01%, 2.4% and 2.6% for diesel, 10%, 20%, 30% and 40% DEE premixed ratios, respectively. COV of maximum cylinder pressure (p_{max}) was also 1.08%, 1.2%, 2.44%, 4.2% and 6.7% for diesel, 10%, 20%, 30% and 40% DEE premixed ratios, respectively. It was concluded that DEE premixed ratio was limited to 40% because of the heavy audible knock.
- It was stated that COV of IMEP values was increased with biodiesel–DEE blends up to 40% DEE ratio. The COV of IMEP values for 30% and 40% DEE with biodiesel were two/three times higher than that of diesel fuel. It was declared that higher variability in COV of IMEP for biodiesel–DEE blends was sourced from deterioration of combustion which was sourced from vapor locks due to evaporation of volatile DEE in the fuel line.
- It was stated that the lower COV of IMEP was obtained with the diesel–biodiesel blend without DEE additive while DEE addition into diesel–biodiesel blend increased cyclic variations, but DEE addition up to 10% into diesel–biodiesel blend did not violently affect the engine stability. It was determined that COV of diesel fuel was around 3% for most engine loads and COV values were lower than 5% for the diesel–biodiesel–DEE blends.
- It was stated that small differences was observed in COV values of pure vegetable oil and vegetable oil–biodiesel blend. A little higher COV values were get by DEE addition to the vegetable oil, biodiesel and their blend, but the COV values obtained with all tested fuels were inside the acceptable limits.

- It was determined that rising ethanol addition to biodiesel fuel gave the more stable combustion and increase of DEE ratio in the ethanol–DEE blend improved combustion stability in a limited range. Higher than 80% ethanol with biodiesel and less than 60% DEE with ethanol did not allow engine operation while 80% DEE and 20% ethanol blend gave the better combustion stability.
- It was determined that reducing of injected main fuel for 0.5% DEE premixed ratio during engine start–up period was raised the stability of combustion (COV of engine speed) during cold start of the diesel engine, but speed–up period was expanded in that case.
- A single cylinder direct injection experimental diesel engine was employed in the most studies on using of DEE. Hence, it will be useful the using of the multi cylinder diesel engines mounted in the vehicle to generalize the findings about DEE for future researches.
- It was understood that DEE addition to different diesel engine fuels generally improves combustion, increases efficiency and reduces the most engine emissions with tolerable power reduction and reasonable increase in fuel consumption, but it is determined that DEE additive especially in high blending ratios increases frequently cyclic variations. Therefore, new methods have been explored the reduction of cyclic variations for future studies when DEE is used as a fuel or fuel additive in internal combustion engines.

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