Biofuel additive production from glycerol and determination of its effect on some fuel properties

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Abstract

In this study, the effects of glycerol ethers as a biobased additive on some important fuel properties of the diesel–bio-diesel blend are investigated. For this, firstly, glycerol ethers are synthesized by the etherification reaction of glycerol with *tert*-butyl alcohol with the presence of Amberlyst-15 as an acidic catalyst. The process of synthesis is followed by analyzing product composition through Fourier-transform infrared spectroscopy and gas chromatography-mass spectroscopy. Lastly, synthesized glycerol *tert*-butyl ethers are mixed with a diesel–biodiesel blend, and the effects of glycerol ethers on the fuel properties are determined. The analysis results show that glycerol *tert*-butyl ether mixture consists of *mono*- and *di*-ethers of glycerol. Due to the dehydration reaction and hindrance effect, the *tri*-ether of glycerol is not generated. The outcomes of determination of fuel properties reveal that glycerol ethers can be blended with a biodiesel–diesel mixture without any significant change in the fuel properties by fully meeting the ASTM D7467 standard, indicating glycerol ethers could serve as a biobased additive to diesel–biodiesel blend.

Keywords Biodiesel · Biofuel additive · Glycerol · Glycerol ethers

1 Introduction

Internal combustion engines that convert the fuel chemical energy through combustion into mechanical energy are the main power supply machines most commonly used in transportation, agricultural, and construction facilities. An internal combustion engine generates mechanical power by burning the fuel inside the cylinders. This process produces exhaust emissions that contain many substances responsible for air pollution that cause serious environmental and health problems. Vehicles used in transportation are the major air pollution producers [1]. They emit a significant amount of carbon monoxide (CO), unburned hydrocarbon (UHC), nitrogen oxides (NO_x), particulate matter (PM), carbon oxide (CO₂), and unregulated emissions such as formaldehyde, acetaldehyde, benzene,

toluene, and xylene [2, 3]. Each of these emissions has extreme hazards on human health and the environment. Also, currently, pollution from vehicles is responsible for about two-thirds of air pollution in the urban area [4, 5]. In order to mitigate the risk of pollutants on health and environment, emissions standards have been enforcing in most countries over the world. As a result of more fuel-efficient engines, after-treatment devices, and fuel processing technologies, the emissions have been substantially reduced [6]. However, increasing the number of vehicles, resulting in no overall reduction in exhaust emissions. Therefore, to mitigate this problem, it is necessary to utilize renewable biofuels instead of petroleum fuels. Among the biofuels, biodiesel has emerged as an alternative renewable fuel to petroleum diesel. Biodiesel is an oxygenated renewable fuel produced from vegetable oils,

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animal fats, or waste oil/fats by a simple chemical process. Biodiesel has numerous advantages over petroleum diesel fuel; (1) it is biodegradable, non-toxic and environmentally friendly fuel, (2) it is a carbon-neutral fuel since the carbon released by burning biodiesel will be absorbed by plants in the photosynthesis process [7], (3) it can play a significant role in reducing exhaust emissions such as carbon monoxide (CO), unburned hydrocarbon (UHC), and particulate matter (PM) [8, 9], (4) it has a high flash point and auto-ignition temperature that makes it safe for transportation, storage, and distribution; and thus it reduces the risk of fire and explosion, (5) biodiesel is compatible with the existing diesel engine technology and fuel storage and distribution infrastructure. The characteristics mentioned above of biodiesel have led biodiesel to be an attractive alternative fuel to petroleum-based diesel fuel. Hence, its consumption has greatly increased in the last two decades. In the period 2000–2018, world biodiesel production has increased about 46 times, from 0.78 billion liters to 36.1 billion liters [10]. Moreover, as seen in Fig. 1, the global biodiesel production will experience sustainable growth in the next years, increasing up to 39 billion liters in 2027 [11]. However, global biodiesel production is foreseen to decrease in the next 3 years mainly because of less favorable export opportunities, reduction in mineral oil prices, and an increase in biofuel feedstock price [12]. Although currently, the major energy source used in diesel engines is from petroleum-diesel fuel, there is an effort to increase the share of biodiesel in total fuel. In 2018, total biodiesel blending with fossil diesel in Europe was 5.8% [13]. Besides, the European Union (EU) has set a 12% renewable fuel blending target on energy bases for the transportation sector by 2030 [14]. Likewise, other countries such as Turkey, the United States, Brazil, Argentina, and Indonesia have developed a project to increase biofuel use in transportation [15, 16]. As a consequence of the increased biodiesel production worldwide, it is inevitable that glycerol production also will increase since glycerol is a by-product in the biodiesel production

process. The glycerol produced during this process is approximately 10 wt% of total biodiesel [17, 18]. If the estimated amount of biodiesel production of 34 million tons is in 2024, approximately 3.4 million tons of glycerol would be generated. This will create a surplus of glycerol that cannot be evaluated related industries, and it may cause a drop in glycerol prices and environmental concerns [17, 19, 20]. Therefore, it is necessary to find a way of recovering the excess of glycerol. In fact, glycerol cannot be directly used as a fuel in diesel engines owing to its improper fuel properties such as high viscosity, high density, high boiling temperature, and immiscibility with diesel fuel. Hence, the use of glycerol in new applications is essential for both environment and sustainable biodiesel production. However, the transformation of glycerol into oxygenated fuel by chemical methods is possible, and it has drawn the interest of many researchers due to its economic benefits [21]. The utilization of glycerol ethers as a fuel additive would increase the percentage of biofuel input in the internal combustion engines, and it makes it easy to reach the biofuel blending target.

Glycerol conversion into oxygenated fuel can be easily accomplished by the etherification reaction [22, 23]. This reaction occurs between glycerol (G) and *tert*-butyl alcohol (TBA) or isobutylene (IB) in the presence of a heterogeneous acid catalyst, giving the glycerol ethers that can be used as a fuel additive [20, 24]. The reaction scheme that shows the equilibrium reactions involved in the etherification of glycerol with TBA is presented in Fig. 2. As seen in reaction scheme, a mixture of five *tert*-butyl ethers of glycerol, namely *mono-tert*-butyl glycerol ether 1 (MTBG1), *mono-tert*-butyl glycerol ether 2 (MTBG2), *di-tert*-butyl glycerol ether 1 (DTBG1), *di-tert*-butyl glycerol ether 2 (DTBG2) and *tri-tert*-butyl glycerol ether (TTBG) are produced. [17, 25, 26]. Also, a small amount of IB is formed by the dehydration of the TBA [27].

Glycerol ethers are a mixture of *mono*-, *di*-, and *tri-tert*-butyl glycerol ethers, however, *di*-ethers and *tri*-ether of glycerol are potential oxygenated fuel additive to diesel, biodiesel, or their mixture [28]. Also, these ethers can improve fuel quality and reduce emissions [20, 28, 29]. Glycerol ethers could also be substitute MTBE (methyl *tert*-butyl ether) and ETBE (ethyl *tert*-butyl ether) that lead to contamination of underground water [30].

The etherification reaction of glycerol by TBA has numerous advantages over isobutylene. TBA is a by-product of polypropylene production. Also, TBA is cheaper than isobutylene, and while the latter is petroleum originated component. Moreover, TBA is a biobased product, and it can also be produced from lignocellulosic biomass [31]. The etherification of glycerol with TBA occurs in a liquid phase, and thus it does not require high pressure and temperature, which increases the chemical processes risk

Fig. 1 Global biodiesel production forecast [11]

Fig. 2 Reaction pathway for the etherification of glycerol with TBA. Adapted from Ref. [17] and Ref. [26]

and cost. Besides, there is no need to use a solvent in the reaction medium for increasing solubility of reactants [25]. Amberlyst-15, as a heterogeneous acidic catalyst, has been widely used in the etherification reaction due to its activity and high ethers selectivity [19, 22, 32]. Moreover, Amberlyst-15 has a solid form that facilitates its separation from reaction products, and its reusability also contributes to decreasing processing costs [26, 32, 33]. Therefore, in this study, TBA and Amberlyst-15 as a catalyst were chosen for the etherification of glycerol.

Although glycerol ethers are proposed as a potential oxygenated fuel additive, limited studies dealing with the effects glycerol ethers on fuel properties are available in the existing scientific literature [24, 34, 35]. In this regard, the objective of this research is to study the effect of the addition of glycerol ethers in the diesel–biodiesel blend on some important fuel properties and also is to determine whether the quality of the fuel was in agreement with the ASTM D7467 standard.

Since glycerol ethers are not commercially available, production and characterization of glycerol *tert*-butyl ethers were also performed. This presented paper provides some outcomes about how glycerol ethers influence some significant fuel properties, and the authors believe that the outcomes of this study could make a noteworthy contribution to the biofuel research area. This paper is organized into four parts. After a brief information about biofuels and current interest in biodiesel, the importance and conversion process of glycerol into biofuel additive is presented in the introduction part. In the material and method section, the methods adopted for the synthesis and characterization of glycerol ethers are described. The findings from spectroscopic studies and the outcomes from the measurement of fuel properties are discussed in the results and discussion section. In the conclusion section, the key findings of this study are summarized. Also, possible future research on the glycerol ethers is suggested.

2 Materials and methods

In this study, glycerol ethers were synthesized by the etherification reaction of glycerol with TBA at the presence of Amberlyst-15 in a stainless steel batch reactor. For this purpose, a stainless steel batch reactor with 500 cm³ volume was designed and manufactured. Glycerol (purity $\geq$ 99%, TEKKİM: a local chemical company in İstanbul, Turkey), TBA (purity $\geq$ 99.5%, Merck), and Amberlyst-15 (dry form, Dow Chemical Company) were the chemicals for the production of glycerol ethers at laboratory scale. The etherification reaction conditions

such as alcohol/glycerol molar ratio, amount of catalyst, reaction time, reaction temperature, and stirring speed, which gives high glycerol conversion and high ether selectivity were determined from the previously published studies [31, 32, 36]. The conditions of the etherification reaction selected for this study are as follows:

- TBA/Glycerol molar ratio: 4:1
- Amount of Amberlyst-15: 7.5 wt%/glycerol
- Reaction temperature: 90 °C
- Reaction time: 3 h
- Stirring speed: 1200 rpm

Fig. 3 The photographic view of the experimental procedure: **a** synthesis of glycerol ethers in the batch reactor, **b** vacuum filtration of Amberlyst-15 from the liquid phase, **c** separation of TBA from

products by rotary type evaporator, **d** purification of glycerol ethers by the distillation process

The reaction procedure was the following: a defined amount of glycerol, TBA, and Amberlyst-15 were loaded into the reactor, and the reactor was purged with nitrogen gas to obtain an inert environment. Then, the reactor was heated up to reaction temperature, and the reaction started immediately by running magnetic stirring. Since reaction temperature was set to 90 °C, and TBA boils at 82.5 °C, the pressure in the reactor increased up to 8 bar. During the reaction, the reactor temperature and pressure continuously was measured by a digital thermometer and an analog pressure gauge, respectively. At the end of the reaction, the reactor was cooled down to room temperature to collect products in the liquid phase. The Amberlyst-15 catalyst was removed from the product by the vacuum filtration method. A two-stage distillation process was performed for purifying the products. Sufficient amounts of glycerol ethers were produced with the same method by repeating experiments. The detailed view of the experimental procedure was given in Fig. 3.

Characterization of produced glycerol *tert*-butyl ethers was performed by Fourier-transform infrared spectroscopy (FTIR) and Gas Chromatography-Mass Spectrometer (GC-MS). Synthesized glycerol ethers were analyzed by FTIR (Perkin Elmer, Spectrum-Two, USA) in the range of 400–4000 cm^{-1} with the resolution of 1 cm^{-1} and GC-MS (Agilent GC-MSD, Model: 7890B GC-5977MSD) analysis. The DB-WAX column (60 m $\times$ 250 μm $\times$ 0.25 μm) was used for analyzing glycerol ethers. Selected chromatographic conditions for GC-MS analysis were given in Table 1.

To investigate the effects of glycerol ethers on some basic fuel properties, produced glycerol ethers were blended with corn oil biodiesel. If all glycerol obtained from biodiesel production were incorporated into glycerol ethers synthesis, a roughly blending ratio of 10% would occur [37]. Therefore, a blending ratio of 10 vol% was chosen in this study. This blending ratio might contribute to sustainable and economic biodiesel production. Produced glycerol ethers were blended with corn oil biodiesel in 10 vol%, and this resulted in a biodiesel–glycerol ethers mixture (10 vol% glycerol ethers + 90 vol% corn oil

Table 2 Test methods used to determine fuel properties

Property	Test method
Density@15 °C	TS EN ISO 12185
Dynamic viscosity	DIN 53015
Cloud point	TS 2834 EN 23015
Cold filter plugging point (CFPP)	TS EN ISO 116
Cetane index	TS EN ISO 4264
Distillation temperature	TS EN ISO 3405

biodiesel). Firstly, this blend was mixed with a magnetic stirrer, and then, to further increase blend homogeneity, an ultrasonic mixing process was applied at 40 kHz for the time duration of 30 min. After that, the glycerol ethers-biodiesel blend was mixed with diesel fuel in the concentration of 20 vol% and this blended fuel designated as B20_GTBEs. At the final stage, B20_GTBEs was obtained with the 20 vol% renewable fraction, containing 80 vol% diesel fuel, 18 vol% corn oil biodiesel, and 2 vol% glycerol *tert*-butyl ethers. B20 (20 vol% corn oil biodiesel was blended with 80 vol% diesel), and pure diesel (D) were selected as reference fuel for comparison. The biodiesel utilized in this study is corn oil biodiesel because of the high volume of corn oil in Turkey. The details of corn oil biodiesel production and its fuel properties that meet standard specifications of EN 14214 and ASTM D 6751 can be found elsewhere [38].

It should be highlighted that fuel quality is an essential factor in reducing harmful exhaust emissions and being compatible with the existing engine technology. Therefore, before its commercialization, fuel specifications of fuel produced must comply with the international fuel standards. Although most of the countries have their fuel standards, EN and ASTM standards widely accepted. In this study, some essential fuel properties of the fuel samples measured according to international test methods. The test methods used to determine fuel properties were given in Table 2.

Table 1 Selected chromatographic conditions for GC-MS analysis

Column	DB-WAX (60 m $\times$ 250 μm $\times$ 0.25 μm) (20–250 °C) max. 260 °C				
Air flow rate	300 ml/min				
H ₂ flow rate	30 ml/min				
He flow rate	1.4 ml/min				
Split ratio	20:1				
Injection volume	0.5 μL				
Oven temperature program	Rate (°C/min)	Value (°C)	Hold time (min)	Run time (min)	
Initial	–	50	10	10	
Ramp 1	4	115	2	28.25	
Ramp 2	15	250	2	39.25

Fig. 4 FTIR spectra of reactants and products

3 Results and discussion

The FTIR spectra of reactants and products were presented in Fig. 4, and the GC–MS chromatogram of the products was shown in Fig. 5. As can be seen in FTIR spectra, a total of 12 peaks appeared in the reactant, while a total of 10 peaks observed in the products. From the FTIR spectra, it can be seen that both reactants and products have peaks that occurred in the range of 3500–3200 cm^{-1} . The observed peak for reactants can be attributed to O–H stretching vibration in alcohol, and the peak appeared in products that can be attributed to

Fig. 5 The chromatogram of the reaction products

O–H bending vibration of water molecules formed by dehydration of *tert*-butanol. The peaks in the range of 3000–2850 cm^{-1} indicate C–H stretching of the alkane group. The peaks at the 1680–1640 cm^{-1} region can be attributed to the C=C stretching vibration of the alkane group. Peaks in the range of 1300–1000 cm^{-1} represent the stretching vibration of C–O, which exists in the alcohols and ethers [39]. In addition, the peaks appeared at 3340.57, 2971.78, 1472.78, 1364.54, 1239.38, 1197.68, 1043.67, 910.70, and 749.11 cm^{-1} in the reactants were shifted to 3370.34, 2973.33, 1472.78, 1366.10, 1240.59, 1196.41, 1023.73, 907.95, and 748.63 cm^{-1} in the products, respectively. Therefore, disappearing of the peaks from the spectrum of reactants at 1380.56, 1112.30, and 674.60 cm^{-1} , and the formation of a new peak at 1647.23 cm^{-1} in the products spectrum confirm the conversion of glycerol into glycerol ethers. The results of the FTIR spectrum are similar to those obtained by Jamróz et al. [40].

The GC–MS analysis was utilized to identify the substances within the reaction products. MS spectra of glycerol *tert*-butyl ethers are unavailable in Masshunter libraries. Therefore, the products were confirmed by the retention time and mass fragmentation pattern with the previously published papers, wherein a detailed spectroscopic study on *tert*-butyl ethers of glycerol is carried out [40, 41]. It can be easily seen in Fig. 5 that eight peaks appeared in the chromatogram. The observed peaks belong to IB, diisobutene (DIB), TBA, DTBG1, DTBG2, MTBG1, MTBG2, and G, respectively. No peak was observed for TTBG and indicating that TTBG did not form. This result is in agreement with earlier reported results [26, 32, 41]. The reason for this is attributed to the steric hindrance [17, 32]. Besides, the formed of water from *tert*-butyl alcohol by dehydration has an inhibition effect on the Amberlyst-15 catalyst, which decreases the formation of high ethers of glycerol [25, 28, 31]. GC–MS results are in close agreement with those obtained by Jamróz et al. [40], Özbay [42], and Paula et al. [41].

EN 14214 and ASTM D 6751 standards are the most referred standards for pure biodiesel. Biodiesel blends

up to 5 vol% must meet the ASTM D957 diesel standard. Diesel–biodiesel blends containing 6–20 vol% biodiesel should meet the ASTM D 7467 that is adopted for diesel–biodiesel blends (greater than 5 vol% and up to 20 vol% biodiesel) quality [43]. Measured fuel properties of B20_GTBes, B20, and D and the minimum–maximum limit fixed by ASTM D 7467 standard presented in Table 3.

Density is one of the critical fuel properties since it directly affects fuel atomization, fuel consumption, and hence engine performance and emissions. The density of B20_GTBes is lower than that of B20. However, B20_GTBes and B20 fuels have a higher density than diesel fuel due to the high density of biodiesel, as expected. Moreover, under the ASTM D7467 standard, the density of the fuel is not limited.

The most important property of the fuel used in diesel engines is the viscosity. Since viscosity has a significant impact on fuel injection and combustion, it directly affects engine performance and exhaust emissions. High viscosity leads to problems with fuel atomization and the air–fuel mixture formation, which results in incomplete combustion and poor engine performance. Also, high viscosity can cause carbon deposits on cylinder walls and can damage fuel injectors and fuel pumps. Dynamic viscosities of the samples at 40 °C were determined by Falling ball viscosimetry (HAAKE™), water bath (HAAKE™), and stopwatch according to DIN 53015 standard. More detail of dynamic viscosity measurement can be found in Refs. [44, 45]. The kinematic viscosity of each sample was determined by dividing dynamic viscosity to the density at the temperature of 40 °C. As seen in Table 3, the kinematic viscosity of the diesel–biodiesel blend was decreased by the addition of glycerol *tert*-butyl ethers. This result is in agreement with the study of Nouredini et al. [35] that showed 20 wt% a blend of glycerol ethers with methyl esters resulted in an 8% reduction in kinematic viscosity. In this study, 2 vol% fraction of glycerol *tert*-butyl ethers in the final fuel (B20_GTBes) resulted in a decrease in kinematic viscosity from 3.27 to 3.15 mm^2/s , which corresponding to a decline in viscosity by 3.7% compared to B20. In addition,

Table 3 The properties of B20_GTBes, B20 fuel, and D with ASTM D 7467 standard

Property	Unit	Uncertainty	B20_GTBes	B20	D	ASTM D 7467
Density@15 °C	kg/m^3	± 0.2	846.0	847.9	836.3	–
Kinematic viscosity@40 °C	mm^2/s	± 0.002	3.15	3.27	2.86	1.9–4.1
Cloud point	°C	± 0.1	–4.0	–4.0	–6.0	–
Cold filter plugging point	°C	± 0.5	–14.0	–14.0	–19.0	–
Cetane index	–	–	52.5	52.0	53.3	40.0 min.
Distillation temperature	T10 (°C)	± 0.1	204.0	217.1	210.0	–
	T50 (°C)	± 0.1	302.3	294.0	274.9	–
	T90 (°C)	± 0.1	342.4	342.8	340.3	343 °C max.

all fuels' kinematic viscosity was found within the ASTM D 7467 standard.

Cloud point (CP) and Cold filter plugging point (CFPP) are the low-temperature properties that affect the fuel system functionality of a diesel engine. CP temperature is the temperature below which wax in fuel forms a cloudy appearance, and it indicates the onset of fuel solidification [46]. CFPP is a cold flow property used to determine the lowest temperature at which a fuel will freely flow through fuel filters in a diesel fuel system. The cold flow properties of B20 fuel was not affected by the addition of glycerol ethers in the fuel. This was due to low glycerol ethers concentration. However, it has been shown that 20 wt% the blend of ethers of glycerol with methyl esters results in a 5 °C reduction in cloud point temperature [29]. Nevertheless, diesel fuel exhibited the lowest CP and CFPP temperature among the fuels. Besides, the limit of cold flow properties is not specified in ASTM D7467 standard.

Cetane number is an indication of a self-burning characteristic of diesel fuel, and it governs the fuel combustion process inside the cylinder. The higher the cetane number, the better the fuel ignitions within the cylinder that leads to higher performance and lower emissions [6]. Measurement of the cetane number is carried out by a standard test using a particular engine. However, it is difficult and costly. Therefore, the cetane index is used as an alternative to the cetane number due to the complexity of the cetane number test, and it is calculated based on fuel density and distillation temperature. It was found that the cetane index of B20_GTBes increased by 0.5 points when compared to B20. Although both B20_GTBes and B20 have a lower cetane index than that of diesel fuel, the cetane number all fuels are full compliance with ASTM D7467.

The evaporation characteristic is one of the critical fuel features that directly affect the fuel economy, engine performance, and emissions of an internal combustion engine. Petroleum-based diesel fuel is a blend of many hydrocarbons, each hydrocarbon has different chemical and physical properties and hence a wide range of boiling temperatures. This is a desired behavior of fuel to obtain controlled and efficient combustion inside the cylinder. To determine the fuel evaporation characteristic, the distillation test is used as a basic test, and extensive information about the fuel can be extracted from the distillation results. The distillation test is performed by measuring the recovery percentage of vaporized fuel as the temperature increases [47]. The test result is a distillation profile temperature versus percentage volume of the evaporated fuel, allow us to interpret the volatility behaviors of the sample fuel. The point of T10, T50, and T90 are temperatures at which 10 vol%, 50 vol%, and 90 vol% of fuel is vaporized, respectively. T10 represents the light hydrocarbons fraction in the fuel, and it is a critical parameter

for cold start engine performance. Still, a low T10 value is not desirable at all engines running conditions since it adversely affects fuel economy and evaporative emissions [48]. T50 is medium distillation temperature representing the medium hydrocarbons fraction in the fuel, and it influences the engine warm-up, the vehicle acceleration performance, and fuel economy. T90 temperature is the high distillation temperature that represents heavy hydrocarbons fraction in the fuel, and it has a significant effect on lubrication oil dilution, the formation of carbon deposits, and particulate matter (PM). The most important impact of glycerol ethers on fuel properties was determined on distillation temperature. It was measured that the low distillation temperature (T10) of the B20 was decreased from 217.1 to 204.0 °C when 10 vol% glycerol ethers incorporated in the biodiesel. The reason for this could be the low boiling point temperature of glycerol ethers. As mentioned above, this could facilitate the cold start performance of the engine, but it could lead to an increase in fuel consumption. However, B20_GTBes resulted in a slightly higher T50 temperature and nearly the same T90 temperature compared to B20. As a consequence, from the distillation temperatures, it could be inferred that glycerol ethers can improve the cold start performance of the engine, however, due to the low T10 temperature of B20_GTBes the fuel economy could be deteriorated with the use of glycerol ethers. Also, the T10, T50, and T90 temperature of B20_GTBes were in line with the limit fixed by the ASTM D7467.

4 Conclusions

In this research, glycerol *tert*-butyl ethers were synthesized by the etherification reaction of glycerol with TBA at the presence of an acidic catalyst, and the produced glycerol ethers were blended with a diesel–biodiesel blend to determine the effects on glycerol ethers on some fuel properties. It was revealed that measured fuel properties of B20 slightly changed except for T10 temperature with the addition of glycerol ethers, and they were full compliance with ASTM D7467. The significant effect of glycerol ethers on determined fuel properties was observed as a decrease in the T10 distillation temperature. All of the findings indicate that glycerol ethers could serve as a renewable oxygenated fuel additive to biodiesel–diesel blends. Evaluation of the biodiesel-based glycerol in oxygenated fuel production could be the solution to the problems that arise from excess glycerol. Also, in this way, biofuel share in transportation can be more easily increased, and this may facilitate reaching a 12 vol% biofuel blending target. Besides, air pollution and other environmental hazards caused by petroleum fuels could be minimized by using

glycerol ethers. As a consequence, the use of glycerol ethers as a fuel additive has a great significance in terms of environmental perspective and sustainable biodiesel production. However, the effects of glycerol ethers on other fuel properties, engine performance, exhaust emissions, and fuel economy should be extensively investigated in future works.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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