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INVESTIGATION OF WASTE TRANSFORMER OIL/BIODIESEL/DIESEL TRIPLE FUEL MIXTURE IN SEARCH OF ALTERNATIVE FUEL

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Keywords

Alternative Fuel, Waste Transformer Oil, Biodiesel, Diesel, Triple Mixture.

Abstract

In this study, triple fuel mixtures were formed by using biodiesel, which is a clean and sustainable fuel produced from waste frying oils (WFO), waste transformer oil (WTO), which is an important waste of electrical transformers and has similar properties to diesel fuel and commercially purchased diesel fuel. Detailed characterization of each component in the mixture was also made. The diesel fuel ratio was kept to a minimum (10% by volume) and the waste transformer oil ratio was mixed at rates ranging from 20% to 100% by volume while creating the triple mixtures. In this study, in which wastes are evaluated and alternative fuel is produced in this way, some important fuel properties of six different fuel mixtures prepared were compared with EN/ASTM standards. Optimum triple fuel mixtures complying with these standards have been determined.

ALTERNATİF YAKIT ARAYIŞINDA ATIK TRAFO YAĞI/BİYODİZEL/DİZEL ÜÇLÜ YAKIT KARIŞIMININ İNCELENMESİ

Anahtar Kelimeler

Alternatif Yakıt, Atık Trafo Yağı, Biyodizel, Dizel, Üçlü Karışım.

Öz

Bu çalışmada, atık kızartma yağlarından (WFO) üretilen, temiz ve sürdürülebilir bir yakıt olan biyodizel, elektrik transformatörlerinin önemli bir atığı olan ve dizel yakıta benzer özelliklere sahip olan atık transformatör yağı (WTO) ve ticari olarak satın alınan dizel yakıt kullanılarak üçlü yakıt karışımları oluşturulmuş, karışımdaki her bileşenin ayrıntılı karakterizasyonu da yapılmıştır. Üçlü karışımlar oluşturulurken dizel yakıt oranı minimumda tutulmuş (hacimce %10) ve atık trafo yağı oranı hacimce %20 ile %100 arasında değişen oranlarda karıştırılmıştır. Atıkların değerlendirilerek alternatif yakıt üretildiği bu çalışmada, hazırlanan altı farklı yakıt karışımının bazı önemli yakıt özellikleri EN/ASTM standartlarıyla karşılaştırılmıştır. Bu standartlara uygun olan optimum üçlü yakıt karışımları belirlenmiştir.

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INVESTIGATION OF WASTE TRANSFORMER OIL/BIODIESEL/DIESEL TRIPLE FUEL MIXTURE IN SEARCH OF ALTERNATIVE FUEL

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Highlights

- An alternative fuel to diesel has been produced
- Different ratios of biodiesel/waste transformer oil/diesel triple mixtures were prepared
- Some important fuel properties of triple fuel blends were investigated
- Optimum triple fuel mixtures complying with relevant standards have been determined

Purpose and Scope
The aim of this study is to produce an alternative fuel to reduce the consumption of diesel fuel, which is a fossil-based, exhaustible fuel. For this purpose, it is to investigate the alternative feasibility of triple fuel mixtures prepared with biodiesel, a clean, sustainable fuel, and waste transformer oil, a waste oil with similar properties to diesel.

Design/methodology/approach
Waste transformer oil supplied from an electricity company, WFO collected from homes and commercially purchased diesel fuel were first characterized through various analyses. Some important fuel properties such as density, kinematic viscosity, heat value, pour and cloud point, acid value, ash and sulfur content of the triple fuel mixtures prepared by keeping the diesel fuel ratio to a minimum (10% by volume) were determined and these properties were compared with EN/ASTM standards. Optimum mixing ratios meeting these standards were determined.

Findings
According to the findings of the study, three triple fuel mixtures were identified as optimum blends considering their compliance with EN/ASTM standards.

Social Implications
This research provides significant contributions to the environment, economy and scientific literature by evaluating waste and reducing diesel fuel consumption.

Originality
In this study, a triple fuel mixture in which wastes were evaluated was developed as an alternative to fossil-based diesel fuel. The compliance of this fuel with the standards was tested. No study was encountered in the literature investigating the alternative feasibility of such a triple fuel.

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1. Introduction

A large part of the energy needed in the world is met from fossil fuels. The limited reserves of these fuels, the serious damage to the environment and the significant increases in oil prices are their most important disadvantages. The unequal distribution of fossil fuels all over the world also causes some economic and political crises among countries. Considering all these disadvantages, researchers are now looking for alternative fuels (Sathish et al., 2023). Many researchers are doing research concerned with the production of alternative fuels from bio-based waste oils such as waste frying oil (Yusuff et al., 2022; Doğan, 2016), waste animal tallow (Öner and Altun, 2009; Rosson et al., 2021) and fossil-based waste oils such as waste motor oil (Dordic et al., 2021) and waste transformer oil (Nabi et al., 2013; Ajay and Viswanath, 2020).

Transformer oils are remarkable oils as an alternative fuel. Their waste potential and calorific value are quite high and they have properties similar to diesel fuel (Behera and Murugan, 2013). The process in the transformer of transformer oils, which is a mineral oil obtained from the refining of crude oil, which is used for cooling in electrical transformers and has very high insulation properties, causes water to form in it. With the increase in the water content of the transformer oil over time, unwanted oxidation reactions occur in the oil and the physicochemical properties of the oil deteriorate. As a result of this process, called oil aging, oil is separated as waste (Dmitriev et al., 2019).

Tons of transformer oil are separated as waste every year. These oils are usually incinerated and have no known significant use. They create significant pollution when thrown into the environment. Considering all these features, waste transformer oils can be considered as fuel, and in this way, significant contributions can be made to both the environment and the economy, considering the high prices of fuel raw materials (Yadav et al., 2020; Vershinina et al., 2018).

The high viscosity of these oils, which seems to be a good alternative fuel, prevents their use as a alone fuel. For this reason, many researchers have used waste transformer oil by mixing it with different fuels in certain proportions. In particular, it is widely used by mixing it with biodiesel, which is a clean, biodegradable, environmentally friendly and renewable fuel produced from vegetable and animal oils (Yadav and Saravanan, 2015; Qasim et al., 2019). In a study, waste transformer oil and biodiesel mixtures in different ratios (B10, B20, B30, B40 and B100) were investigated as an alternative to diesel fuel. The prepared mixtures were tested in a single-cylinder engine and performance and emission evaluations were made and it was concluded that B30 is the best among all mixtures (Ajay and Viswanath, 2020). In another study, transesterified waste transformer oil was mixed with biodiesel produced from waste canola oils at a ratio of 50:50 by volume, and this mixture was then mixed with diesel in different ratios. Engine tests of fuel mixtures called biodiesel-like fuel (BLF) were made and combustion, performance and emission characteristics of these fuels were examined (Qasim et al., 2017). Behera and Murugan examined the engine performance, combustion and emission characteristics of waste transformer oil-diesel mixtures in a compression ignition engine. It was found that when 100% waste transformer oil was used, the characteristics of the engine deteriorated and the optimum mixture was 40% waste transformer oil and 60% diesel mixture (Behera and Murugan, 2013). There are many studies in the literature investigating different fuel mixtures as alternative fuels. However, there is not encountered study on triple fuel mixture using diesel, biodiesel and waste transformer oil.

In this study, triple fuel mixtures consisting of biodiesel, waste transformer oil (WTO) and diesel in different ratios were prepared and some important fuel properties (density, kinematic viscosity, heat value, pour and cloud point, acid value, ash and sulfur content) of these mixtures were investigated. The ratio of diesel fuel, which has increased in value due to decreasing oil reserves, has been kept to a minimum while preparing triple fuel mixtures. Biodiesel, a clean and renewable energy source, was produced from waste frying oils. In this way, waste oils were evaluated and the environmental damage of the triple fuel mixture was tried to be reduced. Waste transformer oils were also evaluated. In this way, the optimum mixing ratio showing the best fuel properties was determined.

2. Materials and Method

2.1. Materials

Waste transformer oils (Figure 1-a) were obtained from an electricity distribution company in Erzurum, Turkey. Diesel fuel was purchased commercially from a fuel company located in Erzurum. Waste frying oils (Figure 1-b) used to produce biodiesel were collected from different houses. Methanol and potassium hydroxide used in biodiesel production were obtained from Merck and Lach-Ner, respectively. The potassium hydroxide solution (0.1 N) in ethanol (Merck) was used to analyze the acid value. Coulometric anode and cathode solutions (Cou-Lo Formula A and Cou-Lo Formula C, GRScientific, U.K.) were used to analyze the water content.

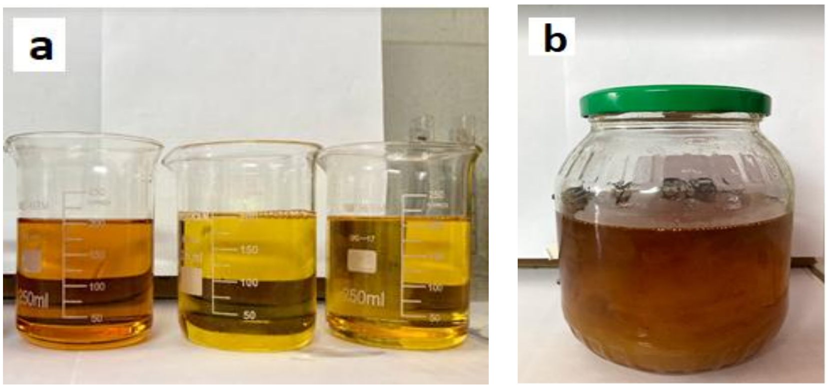

Figure 1. a) Waste transformer oil, b) waste frying oil

2.2. Characterization of Waste Transformer Oil, Waste Frying Oil and Diesel Fuel

The characterization of waste transformer oil (WTO), waste frying oil (WFO) and diesel fuel was carried with the analyzes given in Table 1.

Table 1. Performed analyzes for the characterization of WTO, WFO and diesel.

Type	Analysis
Waste Transformer Oil (WTO)	Density, kinematic viscosity, pour and cloud point, heat value, sulfur, ash and water content
Waste Frying Oil (WFO)	Density, iodine number, saponification number, acid value and fatty acid composition
Commercially Purchased Diesel	Density, kinematic viscosity, pour and cloud point, heat value, sulfur and ash value

The details of the analyzes performed are given in Table 2.

Table 2. Analyzes used in the characterization of waste transformer oils, waste frying oils, biodiesel and diesel fuel

Property Measured	Device/Method	Model	Standard Used
Density (at 15^{o}C)	Automatic density meter	Rudolph Research Analytical, DDM 2909	ASTM D4052
Kinematic viscosity (at 40^{o}C)	Digital constant temperature kinematik viscosity bath	Koehler KV4000 series	ASTM D445
Cloud point	Cloud and Pour Point Bath	SETA (11010-2)	ASTM D2500
Pour point	Cloud and Pour Point Bath	SETA (11010-2)	ASTM D97
Heat value	Calorimeter bomb	IKA C200	ASTM D240
Sulfur content	Carbon sulfur analyzer using an infrared cell	ELTRA CS 580	ASTM D1552
Water content	Karl Fischer coulometric titrator in conjunction with anode and cathode solutions	GR Scientific Cou-Lo Aquamax KF Moisture Meter	ASTM D6304
Ash content	Muffle furnace	Magma Therm	ASTM D482
Acid value	Titration method (using a KOH-ethanol solution)	-	EN ISO 660
Iodine number	Titration method	-	EN ISO 3961
Saponification number	Titration method	-	EN ISO 3657
Fatty acid composition	Gas chromatograph system equipped with an auto-injector	SHIMADZU, QP 2010 and the RESTEK Rtx-Wax capillary column (60 m × 0.25 mm id., 0.25)	EN 14103
Fourier Transform Infrared (FTIR) analysis	FTIR spectrophotometer (in the range of 4000-400cm^{-1})	Bruker VERTEX 70v	-

In the analyses conducted using gas chromatography (GC), the initial oven temperature was set to 140°C and held for 5 minutes. Then, the temperature was increased at a rate of 3°C per minute until reaching 240°C, where it was maintained for 17 minutes.

2.3. Production and Characterization of Biodiesel

Waste frying oils collected from different houses are firstly filtered in order to be purified from the impurities they contain. A certain amount of filtered oil was weighed and placed in a jacketed glass reactor and the oil was converted to biodiesel according to the basic transesterification reaction using methanol in the presence of KOH catalyst. The parameters (6:1 alcohol:oil molar ratio, 1% by weight catalyst amount, 60°C reaction temperature and 2 hours reaction time) were selected considering the literature information while performing the transesterification reaction. The details on biodiesel production and purification are explained in another article (Çelik-Okumuş et al., 2019).

Biodiesel samples synthesized from WFOs collected from households were characterized by analyzing density, kinematic viscosity, cloud and pour points, heating value, and ash content. Additionally, fatty acid methyl ester composition was determined using GC. The devices and models used in these analyses are presented in Table 2.

2.4. Preparation of Waste Transformer Oil/Biodiesel/Diesel Triple Mixtures

In the study, before the triple fuel mixtures were prepared, first a simple filtration process was applied to improve the waste transformer oil and then an adsorption process was applied to remove the water it contained.
It is undesirable for fuels to contain water (Çelik-Okumuş et al., 2019) and therefore, water of waste transformer oils was removed before using them in triple fuel mixtures. Optimum conditions of the adsorption process in which factory tea waste (FTW) was used as adsorbent were determined. Under these conditions, a very large proportion (98.6%) of the water in the WTO was removed. Studies on the adsorption process were described in detail in another article (Karaca and Doğan, 2022).

WTO, biodiesel and diesel fuel were mixed in 6 different volumetric ratios. While determining the mixing ratios, the percentage of diesel fuel, which is the most valuable component of the mixture, was kept to a minimum (10%). The ratios of WTO and biodiesel were changed. In addition, the sample (6) consisting of 100% WTO was also evaluated. The ratios of the prepared triple fuel mixtures are given in Table 3.

Table 3. Ratios of prepared triple fuel mixtures

Type of Fuel	Mixing Ratios (volume %)					
	1	2	3	4	5	6
Biodiesel	70	50	30	20	10	0
Waste transformer oil	20	40	60	70	80	100
Diesel	10	10	10	10	10	0

Some important fuel properties (density, kinematic viscosity, heat value, pour and cloud points, acid value, ash content and sulfur content) of each triple fuel mixture were examined and the most suitable mixture was tried to be determined by considering fuel standards.

3. Results and Discussion

3.1. Characterization of WTO

The properties of waste transformer oil used in forming triple fuel mixtures are given in Table 4.

Table 4. Some properties of waste transformer oil

Property	Unit	Value
Density (at 15°C)	g/cm^3	885.3
Kinematic viscosity (at 40 °C)	mm^2/sn	9.64
Sulfur content	mg/kg	0.89
Ash Amount (%)	-	0.21
Heat value	kj/kg	44.6
Pour Point	°C	-43
Cloud Point	°C	-32
Water content	ppm	55

The density (885.3g/cm^3), heat value (44.6kj/kg) and high kinematic viscosity value (9.64 mm^2/s) of WTO were similar to the values in a study (Rajan et al., 2022) and were consistent with the literature. The 55 ppm water content of WTO is above the maximum allowable amount (50 ppm) and these oils have a very high pour and cloud point as seen in Table 4. Transformer oil is virtually free of corrosive sulfur, which allows its stability to increase (Preethivasani et al., 2021). The low sulfur content of WTO (0.89 mg/kg) in Table 4 also confirms this. Ash content of fuels is also an important parameter and can be considered as an impurity in the structure of the fuel (Karaca and Doğan, 2022). The ash content of WTO (0.21%) is well above the standard value (≤0.02). FTIR analysis of WTO was also carried. The obtained spectrum is shown in Figure 2.

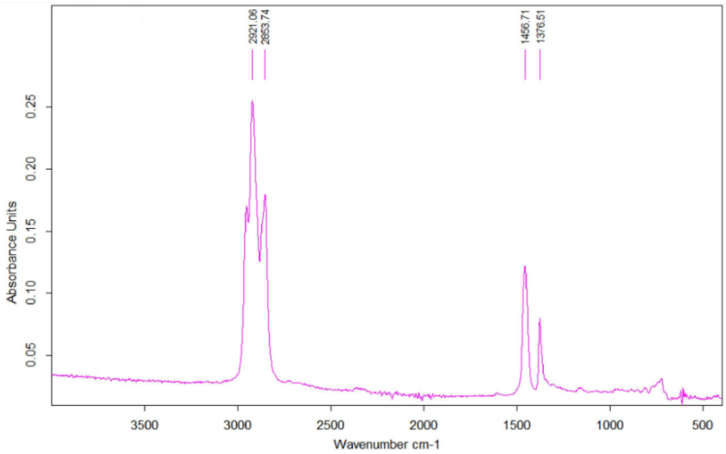

Figure 2. FTIR spectrum of waste transformer oil

The FTIR spectrum of WTO shows two strong peaks at 2921.06 cm^{-1} and 2853.74 cm^{-1}. These peaks are due to the C-H streching bands of methyl and methylene groups. The strong peak at 1456.71 cm^{-1} and the weak band at 1376.51 cm^{-1} in the FTIR spectrum may be attributed to CH_2 asymmetric bending vibration and the CH_3 bending vibration symmetric for methyl groups, respectively (Al-Samaraae et al., 2020).

3.2. Characterization of WFO

Some properties and fatty acid composition of WFO collected from different houses and mixed after filtering are given in Table 5. The gas chromatogram of the WFO is given in Figure 3.

Table 5. Some properties and fatty acid composition of WFO used in biodiesel production

Property	Unit	Value
Density (at 15^{0}C)	g/cm^3	0.9239
Iodine number	g I_2 (100 g)$^{-1}$	120.12
Saponification number	-	185.13
Acid value	mgKOH/g oil	0.73
Fatty Acid Composition		**Concentration (wt. %)**
Stearic acid (C18:0)		3.77
Oleic Acid (C18:1n9c)		32.73
Linoleic Acid (C18:2n6c)		53.37
Palmitic Acid (C16:0)		6.94
Lauric Acid (C12:0)		1.36
Other		1.83

Accordingly, the density and saponification number of WFO were determined as 0.9239 g/cm^3 and 185.13, respectively. These values were similar to those in one study (Sani et al., 2017). The iodine number of WFO (120.12) was equal to the EN standard value (max. 120) and was above the value (116.8) determined by Xu et al. (Xu et al., 2022). The acid value was within EN and ASTM standards.

In addition, when the fatty acid composition of WFO is examined, it is seen that a significant part (86.1%) of the WFO consists of unsaturated fatty acids (oleic acid, linoleic acid). This can often be due to the use of vegetable oils as frying oil. However, it is seen that there are also lower levels of saturated fatty acids (stearic, palmitic, lauric) in the oil.

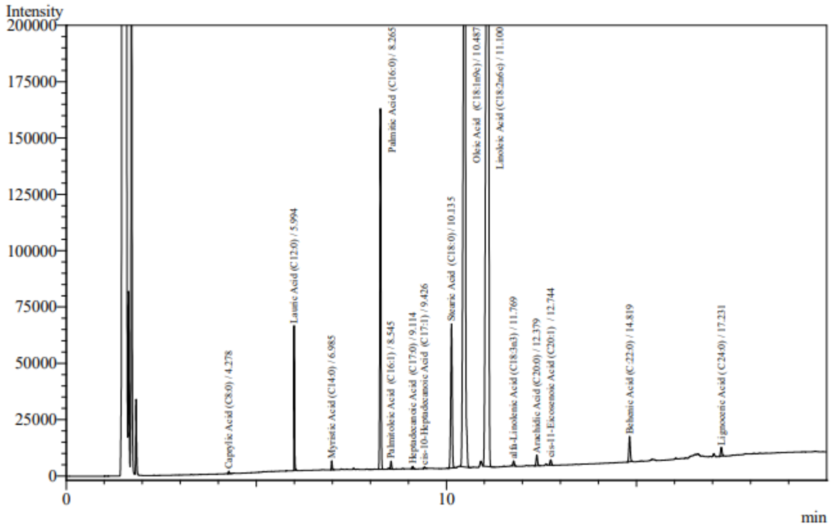

Figure 3. GC spectrum of waste frying oil

3.3. Characterization of Biodiesel and Diesel

Some properties of commercially purchased diesel fuel are also examined and presented in Table 6.

Table 6. Some properties of diesel fuel used in the study

Property	Value
Density (at 15^{o}C, g/cm^3)	0.83
Kinematic viscosity (at 40 ^{o}C, mm^2/sn)	2.7
Cloud point (^{o}C)	-14.8
Pour point (^{o}C)	-28.1
Heat value (kj/kg)	55.3
Sulfur Amount (mg/kg)	1.68
Ash Amount (%)	0.005

Accordingly, the density of diesel fuel at 15^{0}C was the same as that of Kumar et al. (Kumar et al., 2022), and the heat value was higher than the value they found (42.57 kJ/kg). The kinematic viscosity value (2.7 mm^2/s) was almost the same as in the study of Wang et al. (Wang et al., 2020). The low cloud point (-14.8^{0}C) was above their value (-19^{0}C). The pour point was determined as -28.1^{0}C. This value was very close to the value (-26^{0}C) obtained by some researchers (Al-Samaraae et al., 2020). The very low sulfur content of diesel fuel (1.68 mg/kg) was consistent with the results of Kasumba et al.'s study (Kasumba et al., 2019) and the ash content (0.005%) by Gupta and Agarwal (Gupta and Agarwal, 2021). In addition, FTIR analysis of diesel fuel was also carried and the obtained spectrum is shown in Figure 4.

The two strong peaks (2921.74 cm^{-1} and 2853.24 cm^{-1}) and the peak at 1457.74 cm^{-1} seen in the FTIR spectrum of diesel represent C-H streching and C-H bending, respectively. These peaks confirm the presence of alkanes. There is also a weak band (1377.10 cm^{-1}) in the spectrum attributable to the CH_3 bending vibration symmetric for methyl groups. The FTIR results for diese were similar to those reported by Qasim et al. (Qasim et al., 2017).

Biodiesel was produced from WFO by transesterification reaction and some properties of the produced biodiesel were investigated. In addition, fatty acid methyl ester (FAME) composition was determined with the help of GC. The obtained results are given in Table 7 and the gas chromatogram of the biodiesel sample is given in Figure 5.

Accordingly, in the biodiesel produced from WFO, unsaturated fatty acid methyl esters such as linoleic acid (56.46%) and oleic acid (31.27%) were found to be the highest, respectively. Sahar et al. detected the same fatty acid methyl esters in the biodiesel they produced from WFO (Sahar et al., 2018).

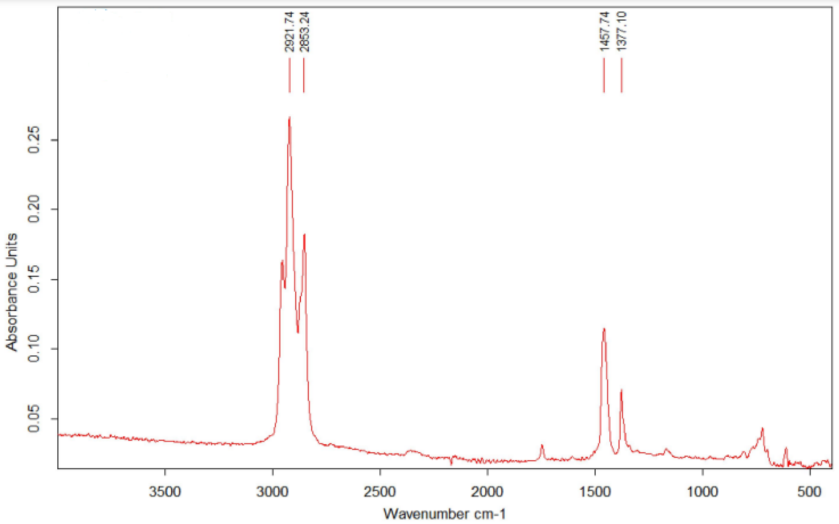

Figure 4. FTIR spectrum of diesel fuel

In addition, the density value of the biodiesel sample synthesized from WFO was determined as 0.8853 g/cm^3 at 15^{0}C and the kinematic viscosity value at 40^{0}C was determined as 3.5 mm^2/s. These values were slightly higher than the density value (870 kg/m^3) and slightly lower than the kinematic viscosity value (4.0 mm^2/s) in the study by Corro et al. (Corro et al., 2019). The heat value was found to be higher than the 38.35 kj/kg value obtained by Arthanarisamy et al. (Arthanarisamy et al., 2020), while the acid value was within the standard ranges, similar to the study by Naeem et al. (Naeem et al., 2022). In addition, cloud and pour points were determined as -2.8^{0}C and -13.5^{0}C, respectively. These values were lower than the values obtained by Nawaz et al. (Nawaz et al., 2021), and close to the values obtained by Soltani et al. (Soltani et al., 2020). It is seen that the ash content of biodiesel, which is 0.01%, is below the relevant standard value (≤0.02) (Gupta and Agarwal, 2021).

Table 7. Some properties and fatty acid composition of produced biodiesel

Property	**Unit**	**Value**
Density (at 15^{0}C)	g/cm^3	0.8853
Kinematic viscosity (at 40^{0}C)	mm^2/sn	3.5
Cloud point	^{o}C	-2.8
Pour point	^{o}C	-13.5
Heat value	kj/kg	39.9
Acid value	mgKOH/g oil	0.78
Ash Amount (%)	-	0.01
Fatty Acid Methyl Ester Composition		**Concentration (wt. %)**
Stearic acid methyl ester (C18:0)		3.64
Oleic acid methyl ester (C18:1n9c)		31.27
Linoleic acid methyl ester (C18:2n6c)		56.46
Palmitic acid methyl ester (C16:0)		6.71
Other		1.92

FTIR analysis of biodiesel produced from WFO was also carried and the obtained spectrum is shown in Figure 6.

The two strong peaks (2921.97 cm^{-1} and 2852.87 cm^{-1}) seen in the FTIR spectrum of biodiesel represent stretching vibrations of $(CH)_n$ (n=1,2,3). The strong peak at 1743.09 cm^{-1} represents the C=O stretching vibration of carbonyl groups present in esters. The peak at 1463.51 cm^{-1} represents C-H bending. The peak at 1162.53 cm^{-1} indicates O-CH_3 stretching, while the weak peak at 722.44 cm^{-1} indicates CH_2 rocking vibration. The FTIR results for biodiesel were similar to those reported by Ali et al. (Ali et al., 2018).

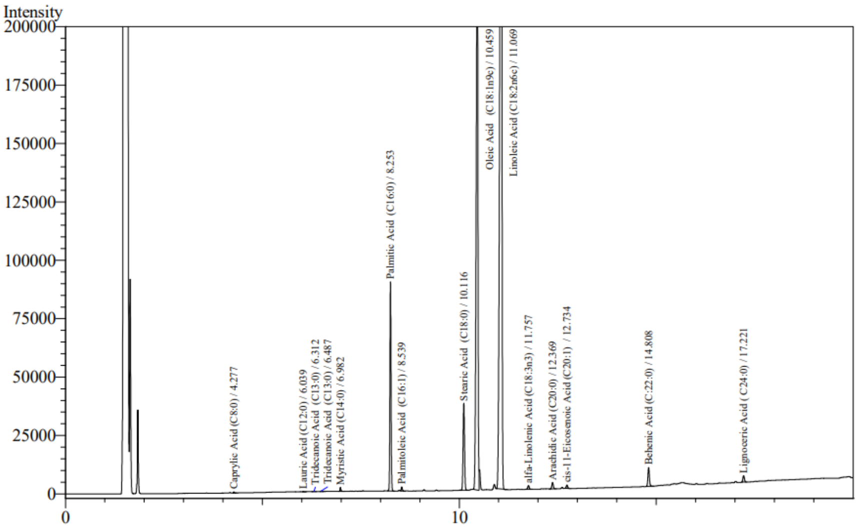

Figure 5. GC spectrum of the biodiesel sample produced from WFO

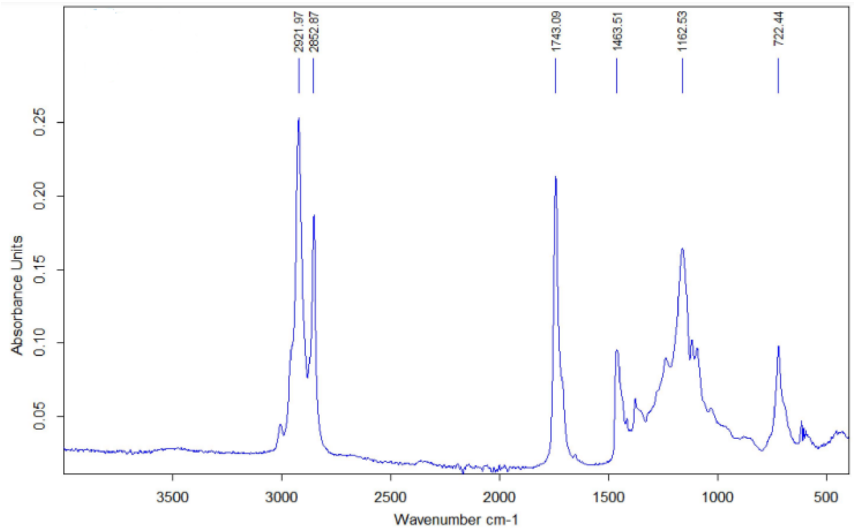

Figure 6. FTIR spectrum of biodiesel

3.4. Investigation of Fuel Properties of WTO /Biodiesel/Diesel Triple Mixtures

At this stage of the study, WTO, which was dehydrated under optimum conditions, biodiesel synthesized from WFO and commercially purchased diesel fuel were mixed in different proportions and triple fuel mixtures were prepared at the mixing ratios given in Table 3. Since our aim here is to keep diesel fuel consumption to a minimum, the ratio of diesel fuel was kept at the lowest level (10%) while preparing the mixtures. On the contrary, the ratio of biodiesel (clean and renewable energy source) and the ratio of WTO, which has a significant potential as waste, were changed. Some important fuel properties such as density, kinematic viscosity, heat value, pour point, cloud point, acid value, ash content and sulfur content of each sample prepared at different ratios were determined and an alternative triple fuel mixture was tried to be determined, which complies with diesel fuel standards. The results obtained are given in Table 8. The fuel properties of 6 samples prepared at different rates were investigated for compliance with EN and ASTM standards.

As seen in Table 8, the density values of the mixtures vary between 0.87 and 0.89 g/cm^3 and comply with the standard ranges. Since the density value is an important property that affects the atomization efficiency of the fuel, it is important that these values comply with the standard ranges (Venkatesan et al., 2019).

The kinematic viscosity values of the samples vary in the range of 2.7-9.6 mm^2/s and increase as the ratio of waste transformer oil in the mixture increases. This is due to the high viscosity of the WTO (T100). The lowest viscosity value (2.7 mm^2/s) belongs to diesel fuel (D100). In a study conducted with diesel fuel and waste transformer oil mixtures, similar results were obtained regarding viscosity values, and kinematic viscosity values increased with the increase of WTO ratio, similar to our study (Behera and Murugan, 2013). Kinematic viscosity is a very important fuel property that shows the fluidity of the fuel. Because a high viscosity fuel is difficult to flow, injection equipment operation and spray atomization will also be difficult (Al-Samaraae et al., 2020). For this reason, it is important for the fuel to have the viscosity values in the standard ranges. Here, it is seen that the kinematic viscosity values of samples 1,2,3, D100 and B100 comply with EN or ASTM standards, but the kinematic viscosity values of samples 4, 5 and 6 are above both standard ranges.

Table 8. Some important fuel properties of triple fuel mixtures

Fuel Property	1	2	3	4	5	6 (T100)	D100	B100	Europe EN 14214	ASTM D 6751
Density, g/cm³	0.88	0.88	0.87	0.87	0.87	0.89	0.83	0.88	0.86 -0.9	0.575-0.90
Kinematic viscosity, mm²/s	4.0	4.8	5.8	6.2	6.2	9.6	2.7	3.5	3.5-5.0	1.9-6.0
Heat value, kj/kg	43.5	47.4	45.5	47.7	47.6	44.6	55.3	39.9	-	-
Pour point, ºC	-22.2	-32.8	-33.4	-39.8	-38.5	- 43	-28.1	-13.5	-	-15 to + 10
Cloud point, ºC	-15.4	-20.9	-19,6	-22.6	-23.6	-32	-14.8	-2.8	-	-3 to + 12
Acid value, mgKOH/g oil	0.77	0.77	0.66	0.60	0.54	-	-	0.78	<0.5	<0.8
Ash Amount, %	0.008	0.012	0.014	0.17	0.2	0.21	0.005	0.01	≤0.02	≤0.02
Sulfur Amount, mg/kg	0.25	0.31	0.78	0.81	0.86	0.89	1.68	-	≤10	≤15

The heat value has a significant effect on the fuel consumption of the engine. High heat value means that the fuel releases higher heat energy during combustion. Similar results to the heat values (39.9-55.3 kJ/kg) obtained for the samples here were also obtained in other studies (Qasim et al., 2017; Kumbhar et al., 2021).

Cloud and pour points are the most important cold flow properties that affect the performance of fuels at low temperatures. As the fuel is cooled, a cloud of wax crystals forms that has the potential to clog fuel filters. The temperature at which this first crystal cloud forms is the cloud point. If the fuel continues to be cooled after this point, the amount of wax crystals increases, the fuel begins to gel and the fuel can no longer be pumped. This temperature is called the pour point (Yunus Khan, 2021). As seen in Table 8, the cloud and pour points of the samples were quite low. Cloud points ranged from -2.8⁰C to -32⁰C, while pour points ranged from -13.5⁰C to -43⁰C. Low pour point and cloud point cause the fuel to perform higher in cold weather (Doğan, 2016). Since the cloud (-32⁰C) and pour points (-43⁰C) of WTO are quite low, it is seen that the pour and cloud points decrease with the increase in the WTO ratio of the samples. Considering the fuel standards here, the low values are a positive situation for all samples.

The acid values of the samples vary between 0.54-0.78 mgKOH/g oil. High acid value is undesirable in fuels as it increases corrosion. Biodiesel contains fatty acids due to its structure (Dharma et al., 2019). Here, it is seen that the acid value increases with the increase in the biodiesel ratio, but the acid values of the samples are in accordance with ASTM standards, although the acid values are above EN standards.

The ash content of the samples varies between 0.008% and 0.21% and increases as the waste transformer oil ratio increases. Since ash is considered as an impurity in the structure, high ash content is undesirable in fuels (Karaca and Doğan, 2022). Here, it is seen that the ash amounts of samples 1,2,3,D100 and B100 comply with both standards, but the ash amounts of samples 4,5 and 6 are above both standard ranges.

Sulfur is one of the most common impurities found in petroleum products in different forms. Sulfur-containing compounds are among the most undesirable components of petroleum, as they cause significant environmental pollution. Therefore, sulfur limits in conventional diesel have been significantly lowered (Margui et al., 2019). The amount of sulfur should be below 10 mg/kg according to the EN standard, and below 15 mg/kg according to the ASTM standard. In the study, as the waste transformer oil ratio of the samples increased, the sulfur content increased from 0.25 to 0.89 mg/kg. However, it was observed that the sulfur content of all samples remained well below the EN and ASTM standard ranges.

When all mixtures are evaluated together, it can be said that fuel properties such as density, heat value, pour and cloud point, acid value and sulfur content were positive for all mixtures. Kinematic viscosity is a key fuel property and in this study only kinematic viscosity values of fuel mixtures 1, 2 and 3 fit within the standard ranges. Similarly, only the ash amounts of samples 1, 2 and 3 are in the standard ranges. It is also noteworthy that the acid values, ash and sulfur amounts of these three samples are lower than the samples 4,5 and 6. For all these reasons, it can be said that the most optimum triple fuel mixture ratios for this study are 1, 2 and 3 mixtures.

4. Conclusion

In this study, in order to develop an alternative fuel to fossil-based diesel fuel, triple fuel mixtures were prepared using biodiesel synthesized from WFO, WTO and diesel at different rates. Detailed characterizations of the components in the triple fuel mixture were made by using analysis techniques such as FTIR, GC, and by examining some fuel properties. Then some important fuel properties (density, kinematic viscosity, heat value, pour and cloud point, acid value, ash and sulfur content) of the triple fuel mixtures prepared by keeping the diesel fuel ratio to a minimum (10% by volume) were determined. Compliance of these properties with EN and ASTM standards was examined.

Conflict of Interest

No conflict of interest was declared by the authors.

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