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Biodiesel Production from Four Residential Waste Frying Oils: Proposing Blends for Improving the Physicochemical Properties of Methyl Biodiesel

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Abstract: The physicochemical properties of biodiesel fuels and their blends prepared from four residential waste vegetable frying oils (sunflower (FSME), canola (FCME), mixture of sunflower and rapeseed (FSRME) and corn (FSCME)) were evaluated and measured to determine the best blend. The results indicate that the stability of 10 biodiesel blends was above 10 h for 0-month, meeting the stability requirement regulated in EN 14214:2014 by adding FSCME, which depends on the concentration amount of FSCME. Besides, the results showed that all fuel samples did not meet the requirements of diesel fuel standards. Therefore, automobile gasoline is used as an additive to unmixed biodiesel in various concentrations to reduce the kinematic viscosity, density and cold flow properties. The results indicate that BG85 and BG80 have met the mixed pure biodiesel with gasoline fulfilled diesel fuel quality standard. Therefore, the samples with stability above 10 h were mixed with gasoline in 15% and 20% to reduce the cold flow properties and meet the specifications of the diesel fuel standards. Moreover, the effect of long-term storage on the properties of all samples was investigated under different storage conditions. The results indicate that higher storage temperatures and longer storage periods negatively influenced the properties of the fuel samples.

Keywords: residential waste vegetable frying oils; automobile gasoline; fuel properties; storage period; storage temperatures

1. Introduction

In recent years, scientific researchers have increasingly been looking for fuel, such as biodiesel, that is renewable, healthier and cleaner-burning than diesel fuel [1,2]. Biodiesel has advantages over diesel oil as it is less polluting, and has a higher cetane number, flash point and lubricity [3,4]. Recently, the research has focused on the production of biodiesel from waste frying oil, which involves the transesterification of oils by short-chain alcohol in the presence of a suitable catalyst [5,6]. In general, biodiesel is produced from a variety of feedstocks possessing different chemical compositions. Thus, the physical and chemical properties of biodiesel, such as kinematic viscosity, density and cold flow properties, are directly dependent on its fatty acid profile and characteristics [7]. Thus, the characteristics of combustion and emissions from engines are varied, and depend on the exact biodiesel used [8–10]. Additionally, according to Verma et al. [11], the oxidation stability and cold flow properties of biodiesel depend on the contents of saturated fatty acids. In addition, the cold flow properties of high-temperature biodiesels lead to engine operability problems. In other words, the amount of saturated fatty acid needs to be reduced to improve its flow behavior at low temperatures. In the literature, various methods have been proposed to improve the cold flow properties and to satisfy both cold flow properties and oxidative stability simultaneously, such as the use of additives [12,13], blending [14,15] and winterization [16,17]. Furthermore, during storage, changes in the chemical and physical properties, such as the viscosity, density, induction period and cold flow properties of biodiesel, can accelerate the degradation in the quality of fuel, and may not be suitable for engine application [18,19].

Several studies have investigated the phenomena of the properties of different biodiesels for various storage periods and conditions. For instance, Moser [20] periodically measured the properties, including the oxidative stability, acid value, kinematic viscosity, low-temperature operability and iodine value, of four biodiesel samples over 12 months at three constant temperatures. The results indicated that oxidation stability was significantly reduced, while acid value and viscosity were increased upon extended storage, with these effects becoming more pronounced at elevated temperatures. It was also noticed that there were no samples that were essentially unaffected by extended storage in term of their iodine value and cold flow properties. Kanca and Temur [21] investigated the effect of storage period on the cold flow properties and viscosity of canola-based biodiesel. The results showed that no significant deterioration was observed in the cold flow properties and kinematic viscosity of biodiesel. Jayaraman and Pugazhvadivu [22] investigated the impact of antioxidants and storage temperatures on the stability of biodiesel and its blends over three various storage periods. It was found that the stability of biodiesel and its blends is influenced by storage temperatures and periods. Moreover, the authors have measured and estimated the properties of biodiesels and their blends prepared from different waste vegetable oils for long-term periods at various storage temperatures. Kassem and Çamur [23] investigated the effects of testing temperature on the properties of biodiesel and its blends prepared from waste frying oil (WFME) and waste canola oil (WCME). The properties were measured at ambient temperature. The results indicated that 25-WFME has the greatest kinematic viscosity and density at 40 °C and 15 °C, respectively, compared to other blends. Kassem and Çamur [24] investigated the effects of long-term storage periods on biodiesel's properties and those of their blends at various storage temperatures. The results indicated that the oxidation stability and flash point were reduced, while the acid value, kinematic viscosity and the density were increased during the storage period. It was also found that the properties of biodiesel and their blends were dependent on the percentage of WFME concentration in the mixture. Kassem et al. [25] examined the effect of storage period and testing temperature on the kinematic viscosity and density of biodiesel and its blends with ultra-low sulfur diesel summer, at a constant storage temperature of 40 °C. The results demonstrated that kinematic viscosity and density were increased upon extended storage by only small increments. Saeed et al. [26] examined the effect of blending biodiesels of various ages on viscosity, density and cold flow properties. The results showed that frying-canola-corn biodiesel has the lowest cold flow properties, compared to other samples.

As a continuation of Kassem and Çamur's studies on the properties of biodiesels and their blends prepared from waste vegetable oils [23–25], the objectives of this work are divided into three parts:

- Study the physicochemical properties, including kinematic viscosity, density, cold flow properties and oxidation stability, of biodiesels and their blends in different proportions to investigate the possibility of producing a mixture that improves the oxidation stability and the other physicochemical properties. In this study, four methyl biodiesel samples are produced from residential waste frying oils. The first sample (FSME) was prepared from residential waste frying sunflower oil, the second sample (FCME) was obtained from residential waste frying canola oil, and the third sample (FSCME) was prepared from the mixture of residential waste frying sunflower and corn oil. The last sample (FSRME) was obtained from a mixture of residential waste frying sunflower and rapeseed oil;
- In order to use biodiesel in diesel engines according to American Standard Test Method (ASTM) D975 and European regulations EN 590 for diesel fuel, the unmixed biodiesels were blended with automobile gasoline in different proportions, varying from 5% to 95% by volume, and the physicochemical characteristics of the samples were also evaluated in order to determine the

optimum concentration amount of gasoline. Moreover, biodiesel blends were mixed with the optimum concentration amount of gasoline so as to reduce the kinematic viscosity, density and cold flow properties of the biodiesel;

- We investigate the effects of long-term storage periods on the properties of all fuel samples, including kinematic viscosity, density, cold flow properties and oxidation stability, with different storage temperatures (5 °C, room temperature, RT, (23 ± 1 °C) and 40 °C). These storage temperatures were selected based on expected average weather temperatures in the winter, spring, summer and autumn seasons.

2. Materials and Methods

This section aims to describe the preparation process of the biodiesels, their blends and the gasoline samples, and measure their properties according to ASTM standards. It also discusses the storage test procedures under various storage temperatures for the fuel samples. A flowchart given in Figure 1 illustrates the analysis procedure of this study.

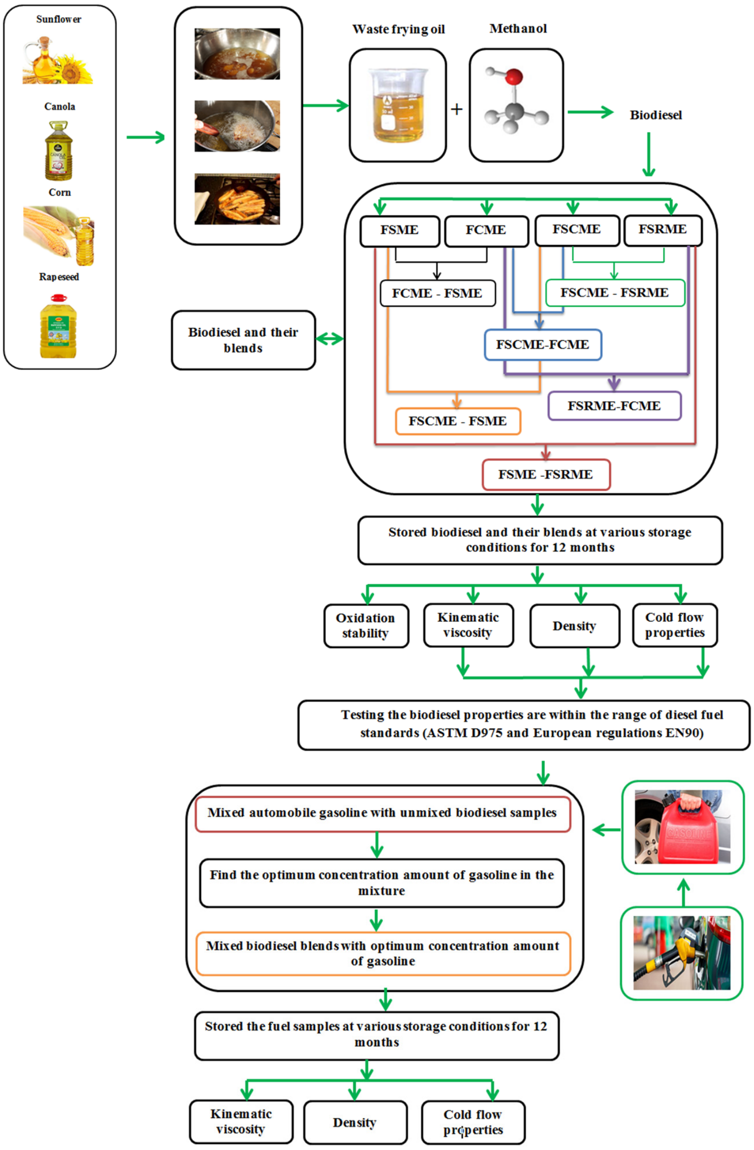


Figure 1. Flowchart of analysis procedure in the present study.

2.1. Preparing Biodiesel Sample

In this study, four different refined vegetable oils, including sunflower, canola, corn and rapeseed oil, were purchased from various companies in Northern Cyprus and Turkey. To obtain residential waste frying oil, the refined oils are used for the frying process, i.e., the frying cooking oil sample was obtained by way of collection after use for cooking various dishes including animal fats and vegetables. The base-catalyzed one-step transesterification reaction method was used to produce biodiesel samples. Biodiesel production was discussed in Reference [24]. In this work, four different samples of the frying cooking oil methyl ester, with significantly different compositions, were prepared. These samples were prepared as follows:

- FSME was prepared from frying cooking sunflower oil;
- FCME was obtained from frying cooking canola oil;
- FSCME was produced from a mixture of frying cooking sunflower and corn oils;
- FSRME was prepared from a mixture of frying cooking sunflower and rapeseed oils.

2.2. Biodiesel Characterization

The samples were analyzed by gas chromatography (GC) and the analysis was carried out according to EN ISO 5508 standard. The biodiesel analysis was discussed in Reference [24]. In general, saturated (Cn:0), monounsaturated with one double bond (Cn:1), and polyunsaturated with two or three double bonds (Cn:2,3) are considered the types of fatty acids that can be present in a triglyceride molecule. The required formulas used for estimating monounsaturated (MUFAMEs), polyunsaturated (PUFAMEs) and saturated (SFAMEs) Fatty Acid Methyl Esters (FAMEs) are given in the below equations.

$$\sum \text{MUFAMs} = \text{C16}:1 + \text{C18}:1 + \text{C20}:1 \tag{1}$$

$$\sum \text{PUFAMs} = \text{C18}:2 + \text{C18}:3 \tag{2}$$

$$\sum \text{SFAMs} = \text{C12}:0 + \text{C14}:0 + \text{C18}:0 + \text{C20}:0 + \text{C22}:0 \tag{3}$$

Based on the fatty acid distribution, the degree of unsaturation (DU) and the long-chain saturated factor (LCSF) are two additional parameters that can be calculated for biodiesel samples.

$$\text{DU} = [\text{monounsatuarted Cn}:1] + 2[\text{polyunsaturated Cn}:2,\ 3] \tag{4}$$

$$\text{LCSF} = 0.1 \times [\text{C16}:0] + 0.5 \times [\text{C18}:0] + [\text{C20}:0] + 1.5 \times [\text{C22}:0] + 2 \times [\text{C24}:00] \tag{5}$$

The fatty acid compositions of the biodiesel samples are listed in Table 1. It can be seen that FSME has the highest saturated fatty acid content. FSCME and FSRME are in the second and the third positions, respectively. It can also be seen that FCME has the highest mono-unsaturated biodiesel composition and FSME has the lowest poly-unsaturated content, and that the FCME has the highest DU while FSCME and FSRME are in the second and the third positions, respectively. Table 2 shows the properties of all the biodiesel samples produced from four frying cooking vegetable oils, and the specification values given in the ASTM D6751 biodiesel standard. It was found that the measured fuel properties are within the limits of ASTM D6751.

Table 1. Fatty acid compositions of fresh biodiesel samples.

Composition (wt. %)	FCME	FSME	FSCME	FSRME	Literature Data [23]	
					Min	Max
C8:0	0.00	0.05	0.15	0.00	-	-
C10:0	0.00	0.33	0.16	0.00	-	-
C12:0	0.08	1.18	2.06	0.00	0.0	49.2
C14:0	0.00	0.10	1.05	0.00	0.0	25.9
C16:0	5.63	37.29	13.62	21.47	0.9	44.1
C16:1	0.00	0.00	0.45	0.09	-	-
C18:0	1.57	4.04	4.65	2.75	0.3	23.5
C18:1	63.97	40.42	50.75	46.18	1.8	92.5
C18:2	20.34	16.84	20.28	25.17	0.0	77.3
C18:3	6.99	0.18	5.20	3.99	0.0	72.3
C20:0	0.46	0.00	0.44	0.51	0.0	7.5
C20:1	1.46	0.00	0.87	0.44	0.0	66.5
C22:0	0.00	0.00	0.00	0.14	-	-
C24:0	0.00	0.00	0.00	0.13	-	-
MUFAMEs	65.43	40.42	52.07	46.71	-	-
PUFAMEs	27.33	17.02	25.48	29.16	-	-
SFAMEs	7.74	42.61	21.82	24.87	-	-
DU	120.09	74.46	103.03	105.03	-	-
LCSF	1.81	5.75	4.13	4.50	-	-

Table 2. Properties of pure biodiesel and their mixtures according to ASTM D6751 biodiesel standard.

Property	Unit	Test Method	Limits	FCME	FSME	FSCME	FSRME
Kinematic viscosity at 40 °C	mm^2/s	ASTM D445	1.9–6.0	4.55	4.62	4.33	4.59
Density at 15 °C	kg/m^3	ASTM D854	867 min.	895.44	875.19	910.42	881.63
Cloud Point	°C	ASTM D2500	Report	−2.0	10.0	7.0	−1.2
Cold Filter Plugging Point	°C	ASTM D6371	Report	−6.0	7.5	4.5	−3.0
Pour Point	°C	ASTMD97	Report	−10.0	5.5	1.6	−6.0
Acid value	mg KOH/g	ASTM D664	0.5 max.	0.35	0.37	0.3	0.4
Oxidation Stability (at 110 °C)	h	EN 14112:2003	3.0 min.	7.5	7.85	14.0	8.27
	h	EN 14112:2014	8.0 min.				

2.3. Fuel Samples

In this study, the biodiesel samples are blended with automobile gasoline to improve the properties of the biodiesel, especially the kinematic viscosity and cold flow properties. Automobile gasoline was purchased from local petrol station. The physico-chemical properties for fuel, and the corresponding standard measurement methods, are listed in Table 3.

Table 3. Physical properties of gasoline.

Property	Unit	Test Method	Limits	Results
Density at 15 °C	kg/m^3	ASTMD 4052	720–775	740.94
Viscosity at 40 °C	mm^2/s	EN ISO 3104	-	0.59
Oxidation stability	minute		>360	-
Cloud point	°C	ISO 3015	-	−57
Pour point	°C	ASTM D6749	-	−57
Octane number, Mon		ASTM D2700	85.0–...	85.1
Octane number, Ron		ASTM D 2699	95.0–...	95
Evaporated at 70 °C	VOL PCT	ASTM D86	22.0–50.0	41.4
Evaporated at 100 °C	VOL PCT	ASTM D86	46.0–71.0	58.6
Evaporated at 150 °C	VOL PCT	ASTM D86	75.0–...	81.9
Distillation residue	VOL PCT	ASTM D86	...–2	1

2.4. Preparation of Blends

In this study, four fresh biodiesel blends were mixed among each other at various percentages, from 20% to 80% (*v*/*v*) in steps of 20% (*v*/*v*), and homogenized with the aid of a magnetic stirrer for 30 min. The following binary mixtures were prepared: FCME–FSME, FSRME-FSCME, FCME-FSRME, FCME-FSCME and FSME–FSRME, at various percentages.

Moreover, a series of blends was prepared by blending gasoline with pure biodiesel samples. The percentage of gasoline added to the biodiesel varied from 0% to 5%, 7%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, 95% and up to 100% by volume. To confirm the homogeneous mixing, samples were stirred with a magnetic stirrer for 10 min.

2.5. Storage Conditions

Finding a suitable storage container is necessary, particularly for long-term biodiesel-petrol blends. In this study, glass containers were selected due to the fact that they would not react with the biodiesel and its blends, and also that they make it possible to create different storage conditions. Before filling the containers with the fuel samples, they were cleaned with acetone and left open for a day. Additionally, the samples were filled only up to half of the total volume of the container to avoid contact with the metal lids of the containers. To evaluate the effect of storage conditions on the biodiesels' properties, the samples were stored under three storage conditions (5 °C, room temperature (23 ± 1 °C) and 40 ± 1 °C) for a period of 12 months.

- For the storage condition of 5 °C, the samples were stored in the refrigerator in which the temperature was fixed at 5 °C.
- For room temperature, the fuel samples were stored in a glass container where the average daily temperature was about 23 °C.
- For the storage condition of 40 °C, the samples were in a temperature-controlled laboratory oven in which the thermostat was used to control the temperature inside the oven and keep it constant.

To ensure that the temperature of storage remains constant, the temperature of the storage refrigerator/oven was measured twice a day. It should be noted that the samples were stored in a dark environment. The properties of the fuel samples were determined bimonthly.

2.6. Analytical Methods

The biodiesel properties of the products obtained from the frying cooking oils were estimated according to the American Society for Testing and Materials standards (ASTM). The kinematic viscosity and density were measured using a Ubbelohde viscometer and a pycnometer with a bulb capacity of 25 mL, respectively. The kinematic viscosity and density were measured at various temperature ranges. The reported data are the averaged values of three measurements at each temperature. Moreover, the cold flow properties in terms of cloud point (CP) and pour point (PP) were measured for each biodiesel sample. Furthermore, the oxidation stability for all biodiesel samples was measured. The quality of biodiesel was examined according to ASTM 6751 and EN90, which are well-accepted biodiesel standards and testing methods. The experimental setup used to measure the biodiesel properties is described in References [23,24].

3. Results and Discussion

3.1. Preliminary Physical Properties of Pure Biodiesel and Blends at 0-Month

The measured kinematic viscosities (KV) and densities (D) of biodiesels and their blends with various volume fractions (VF), at atmospheric pressure and testing temperatures of 40 °C and 15 °C, are listed in Table 4. It can be observed that the viscosity and densities of all samples are within the range of the ASTM D445 and ASTM D854. Generally, according to standard mixing rules for FAME mixtures, the viscosities of the biodiesel blends do not vary greatly from these values for different mixture compositions. It was found that the viscosity and density of EFSCME–FSRME blends and FSCME–FSME blends are within the range of the kinematic viscosity of pure samples. The viscosities of EFSCME–FSRME and FSCME–FSME blends and the FSCME–FSME mixture increased as the amount of FCME and FSME increased in the blend, respectively. This observation can be supported by other scientific studies. For example, Mejía et al. [27] measured the kinematic viscosity of binary mixtures of castor oil biodiesel and palm oil biodiesel at 40 °C. It was found that increasing the amount of castor oil biodiesel in the mixture led to an increase in the kinematic viscosity. Based on the analysis, it can be noticed that 40-FSME has a greater kinematic viscosity compared to pure biodiesels (FSME and FCME) and other blends (20-FSME, 60-FSME and 80-FSME). Additionally, it was found that 20-FCME has a greater viscosity compared to other samples of the FSME–FSRME mixture. Furthermore, 60-FCME and 20-FSRME have the highest viscosities, with value of 4.59 mm^2/s and 4.65 mm^2/s, compared to other blends of FSCME-FCME and FSME–FSRME, respectively. A similar observation is obtained in References [23,24,26]. Kassem and Çamur [23] found that 25-WFME (75% of canola oil biodiesel and 25% of frying oil biodiesel) has the maximum kinematic viscosity, with a value of 5.749 mm^2/s compared to pure samples (WCME = 4.678 mm^2/s and WFME = 4.666 mm^2/s) and other blends. Kassem and Çamur [24] noticed that the maximum values observed for kinematic viscosity occurred with 35 vol% WFME in the admixture. It was found that the kinematic viscosities of WCME, WFME and 35-WFME were 4.545, 4.622 and 5.574 mm^2/s, i.e., the kinematic viscosity increased by 1.029 mm^2/s, to a maximum of 35 vol% WFME WCME/WFME. Saeed et al. [26] found that blending 50 vol% WCME1 with 50 vol% WCME3 gave the highest kinematic viscosity of 4.501 mm^2/s, compared to the pure sample (WCME1 = 4.464 mm^2/s and WCME3 = 4.403 mm^2/s) and other blends. The results indicated that kinematic viscosity increased by 0.097 mm^2/s to a maximum at 50 vol% WCME3. However, this study reports the following:

- The kinematic viscosity increased by 0.04 mm^2/s to a maximum at 40 vol% FSME in FCME–FSME blends
- The kinematic viscosity increased by 0.04 mm^2/s to a maximum at 60 vol% FSME in FSCME–FSME blends
- The kinematic viscosity increased by 0.06 mm^2/s to a maximum at 20 vol% FSME in FSME–FSRME blends
- The kinematic viscosity increased by 0.09 mm^2/s to a maximum at 20 vol% FCME in FSRME–FCME blends

Table 4. Measured kinematic viscosity (KV) at 40 °C and densities (D) at 15 °C for all samples.

Blend	Designation	VF [%]	KV [mm^2/s]	D [kg/m^3]	Blend	Designation	VF [%]	KV [mm^2/s]	D [kg/m^3]
FCME–FSME	FCME	100–0	4.55	895.44	FSCME–FCME	FSCME	100–0	4.33	910.42
	20-FSME	80–20	4.58	879.77		20-FCME	80–20	4.37	907.42
	40-FSME	60–40	4.66	902.18		40-FCME	60–40	4.42	904.43
	60-FSME	40–60	4.64	892.34		60-FCME	40–60	4.59	912.93
	80-FSME	20–80	4.63	882.50		80-FCME	20–80	4.57	903.44
	FSME	0–100	4.62	875.19		FCME	0–100	4.55	895.44
EFSCME–FSRME	FSCME	100–0	4.33	910.42	FSME–FSRME	FSME	100–0	4.62	875.19
	20-FSRME	80–20	4.36	904.64		20-FSRME	80–20	4.65	892.28
	40-FSRME	60–40	4.49	898.96		40-FSRME	60–40	4.63	887.76
	60-FSRME	40–60	4.51	893.16		60-FSRME	40–60	4.61	885.85
	80-FSRME	20–80	4.57	887.42		80-FSRME	20–80	4.60	883.32
	FSRME	0–100	4.59	881.63		FSRME	0–100	4.59	881.63
FSRME–FCME	FSRME	100–0	4.59	881.63	FSCME–FSME	FSCME	100–0	4.33	910.42
	20-FCME	80–20	4.63	900.95		20-FSME	80–20	4.37	903.37
	40-FCME	60–40	4.60	892.15		40-FSME	60–40	4.43	896.33
	60-FCME	40–60	4.58	889.94		60-FSME	40–60	4.48	889.28
	80-FCME	20–80	4.56	886.10		80-FSME	20–80	4.55	882.24
	FCME	0–100	4.55	895.44		FSME	0–100	4.62	875.19

KV: Kinematic viscosity at 40 °C; VF: Volume fraction of the fuel; D: Density at 15 °C.

These deviations from standard mixing rules cannot be explained by variations in the fatty acid concentration profiles in the mixtures. Thus, this observation can be explained based on fundamental aspects of fuel chemistry, i.e., the properties of residential waste frying oils depend on the conditions of frying. Doğan [28] investigated the effects of cooking conditions, including salt content, water content, cooking time and cooking temperature, on the kinematic viscosity of biodiesel prepared from sunflower, corn and canola vegetable oils. The results indicated that the viscosity significantly deteriorates when the salt content, water content, cooking time and cooking temperature of cooking oils are increased. In order to ensure that the density and kinematic viscosity have the same investigation conditions, the determined dynamic viscosities at 40 °C are shown in Figure S1 in the supplementary material. It can be noted that the dynamic viscosities (Dy) of all samples were calculated by multiplying the experimental results of density and kinematic viscosity. It was found that dynamic viscosity has the same characteristics as the kinematic viscosity for all samples.

Referring to Table 4, the kinematic viscosities were measured for unmixed biodiesel at only 40 °C. At these temperatures, these values deviated from the kinematic viscosity of unmixed biodiesel (FCME, FSME, FSCME and FSRME) by values ranging from 0.03 to 0.22 mm^2/s. This evidence suggests that the kinematic viscosities of pure biodiesels are nearly equivalent, an observation that is supported by the results in Table 4. Given these considerations, it is difficult to attribute to the results for mixtures at 40 °C, showing large increases in viscosity up to maximum values at ~60 vol% FSME in FSCME–FSME blends, ~20 vol% FSME in FSME–FSRME blends and ~20 vol% FCME in FSRME–FCME blends, variances in the fatty acid composition of the methyl esters. To ensure that the same phenomena were taking place in the mixtures at various testing temperatures, the kinematic viscosity and density were measured at various temperatures (−10 °C to 300 °C). Figures S2 and S3 in the supplementary material show the measured values of kinematic viscosity and the densities of all samples within a temperature range from −10 to 300 °C. It can be observed that viscosity and density decrease as the testing temperature increases. In addition, the variations in kinematic viscosity ($\Delta\nu$) at low and high temperatures are estimated to ensure that the same tendency occurs at all temperatures. For instance, Figure S4 in the supplementary material shows the variations in kinematic viscosity at 20 °C and 160 °C for some selected samples. It can be observed that the variation in kinematic viscosity ($\Delta\nu$) at low temperatures is very clearly higher than the variation in kinematic viscosity ($\Delta\nu$) at high temperatures. Furthermore, at high temperatures, thermal degradation may be taking place that ameliorates the phenomena, resulting in little or no maxima being observed in the curves.

3.2. Influence of Storage Period, with Various Storage Conditions, on Oxidation Stability

As seen in Table 5, the initial values of the induction period (IP) for FCME, FSME, FSRME and FSCME were 7.5, 7.85, 8.24 and 14.00 h, respectively. In comparison to the oxidative stability requirements of ASTM D6751 and EN 14214, all the methyl esters were above the minimum limit specified in ASTM D6751 (>3.0 h) and EN 14214 (>6.0 h). In general, the amount of unsaturation present in the alkyl esters directly influences the oxidative stability of biodiesel [29–33]. Furthermore, the more unsaturated biodiesels are more susceptible to degrading and forming insoluble products [34,35], and the oxidative stability of the biodiesel decreases with the increasing content of polyunsaturation [36]. During the period of storage, we expect a decrease in this parameter, but there was a slight decrease in the induction time over the 12 months of study for the storage temperature (ST) of 5 °C, as shown in Table S1 in the supplementary material. Furthermore, all the biodiesel samples remained above the minimum limit of EN 14214 for the duration of the study at storage temperature (ST) of 5 °C, except for FSRME (oxidation stability fell below the minimum specification of EN 14214 after 10 months). At room temperature (23 ± 1 °C) and 40 °C, it is noticeable that the stability of the biodiesel samples sharply decreased (Table S1 in supplementary material). This observation can be supported by other scientific researchers who investigated the effect of the storage period under various conditions on biodiesel–diesel blends [35,36].

Moreover, it is noticeable that mixing biodiesels with various concentrations improved the stability of the fuel. It was found that the maximum values observed for IP at 60 vol% FCME in the mixture of FSCME–FCME, i.e., mixing FSCME with FCME, the IP increased by 5.83 h at 60 vol% FCME (Table S1 in the supplementary material). Additionally, it was observed that mixing FSCME with FCME, FSME and FSRME in varying amounts to form the mixture improved the stability of the sample. Over a long time, a serious risk of degradation and the formation of oxidation products may degrade fuel quality, and possibly result in engine damage. Thus, the improvement of a biodiesel's storage stability allows it to be kept for a long-term storage period [37]. Generally, storage stability can be influenced by storage conditions. Based on the oxidation stability specifications listed in the newly released EN 14214:2014, the minimum specified limit of 8 h is required to ensure satisfactory biodiesel stability. In the case of EN 14214:2014, FSCME samples after 6 months and 2 months at room temperature (23 ± 1 °C) and 40 °C were no longer above the minimum oxidative stability specification, while they remained above the limit for the duration of the study at 5 °C, as shown in Table S1 in the supplementary material. Furthermore, FCME and FSME were below the minimum of 8 h, and FSRME fell below the 8 h minimum at 2 months for all storage temperatures (Table S1 in the supplementary material). It was concluded that adding FSCME to other biodiesel samples in varying percentages is sufficient to stabilize FSME, FCME and FSRME over a long storage period at various storage temperatures.

Table 5. Measured induction period for all fresh samples.

Blend	VF [%]	IP [h]	Blend	VF [%]	IP [h]
FCME–FSME	100–0	7.50	FSCME–FCME	100–0	14.00
	80–20	7.95		80–20	12.70
	60–40	8.19		60–40	11.40
	40–60	7.90		40–60	13.33
	20–80	7.87		20–80	10.30
	0–100	7.85		0–100	7.50
FSCME–FSRME	100–0	14.00	FSME–FSRME	100–0	7.85
	80–20	12.85		80–20	8.59
	60–40	11.71		60–40	8.47
	40–60	10.56		40–60	8.40
	20–80	9.42		20–80	8.34
	0–100	8.27		0–100	8.27
FSRME–FCME	100–0	8.27	FSCME–FSME	100–0	14.00
	80–20	8.62		80–20	12.77
	60–40	7.96		60–40	11.54
	40–60	7.81		40–60	10.31
	20–80	7.65		20–80	9.08
	0–100	7.50		0–100	7.85

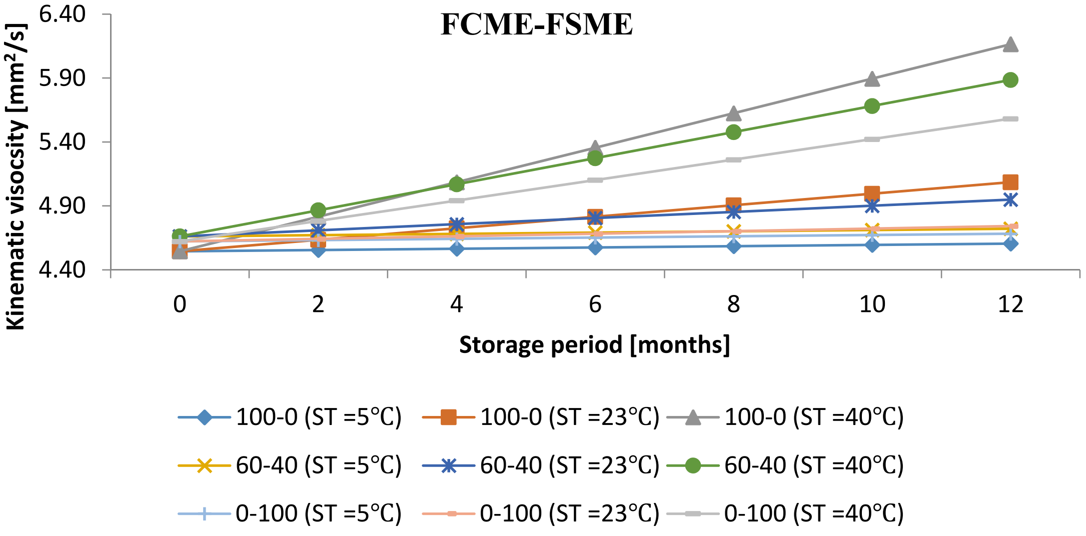
IP: Induction period; VF: Volume fraction of the fuel.

3.3. Impact of Storage Period under Various Storage Conditions on Kinematic Viscosity

Figure 2 illustrates the kinematic viscosities of some selected biodiesel and their blends, measured at 40 °C. Additionally, the experimental results of the test of the kinematic viscosities of biodiesel samples, as a function of storage temperatures (ST) and storage periods (SP) at 40 °C, are summarized in Table S2 in the supplementary material. It was observed that the viscosities for all samples increased as the SP increased, for all storage conditions. It was also found that the higher the ST, the higher kinematic viscosity obtained. In general, among the negative implications of biodiesel oxidation, we can highlight the increase in viscosity due to the formation of gum during the storage period of biodiesel [38]. Moreover, it was found that the kinematic viscosities of biodiesels varied in the range of 4.33–4.62 mm^2/s. Given the ASTM D445 standard, requiring that viscosity values at 40 °C be higher than 1.9 mm^2/s, all the biodiesel samples fulfill this requirement for all storage periods at all storage temperatures, except for FCME, the kinematic viscosity of which was above the maximum limit of viscosity specified in the ASTM D455 after 10 months at an ST of 40 °C. Moreover, the obtained kinematic viscosity data for all unmixed biodiesel samples correspond with the recommended EN 14214 values (3.5–5.0 mm^2/s) at 40 °C for the storage period of 12 months, with an ST of 5 °C. Additionally, storage over an extended period (2, 4 and 6 months) at an ST of 40 °C resulted in a precipitous increase in the kinematic viscosity of FCME, FSME and FSRME, respectively. Additionally, as reported in Table S2, the viscosity of FSCME remained within the range of 3.5–5 mm^2/s over the study's duration, at an ST of 40 °C. Furthermore, data from Table S2 show that the kinematic viscosities of all samples were not in accordance with the standard demand for diesel fuels (ASTM D975 recommended values: 1.9–4.10 mm^2/s). Furthermore, the kinematic viscosity values of FSCME and some blends fulfil the European regulations EN 590, which establishes that viscosity at 40 °C must be in the range of 2.0–4.5 mm^2/s, as shown in Table S2.

The comparison of kinematic viscosity results is facilitated by the introduction of the increase ratio (Ir). This is defined as the expression (Equation (6)) below. The value of Ir should be greater than 1 because the kinematic viscosity of the biodiesel increases with time. It was observed that the values of Ir were greater than 1 for all the biodiesel samples, as shown in Table S2. It was also found that the value of Ir increases as the storage temperature increases. For example, the values of the Ir of FCME at the ST of 5 °C, RT (23 ± 1 °C) and 40 °C were 1.01, 1.12 and 1.36, respectively (see Table S2 in the supplementary material).

$$I_r = \frac{\text{Kinematic visocsity of agiven sample at 12 months of storage}}{\text{Inital value of kineamtic visocsity of agiven sample}} \quad (6)$$



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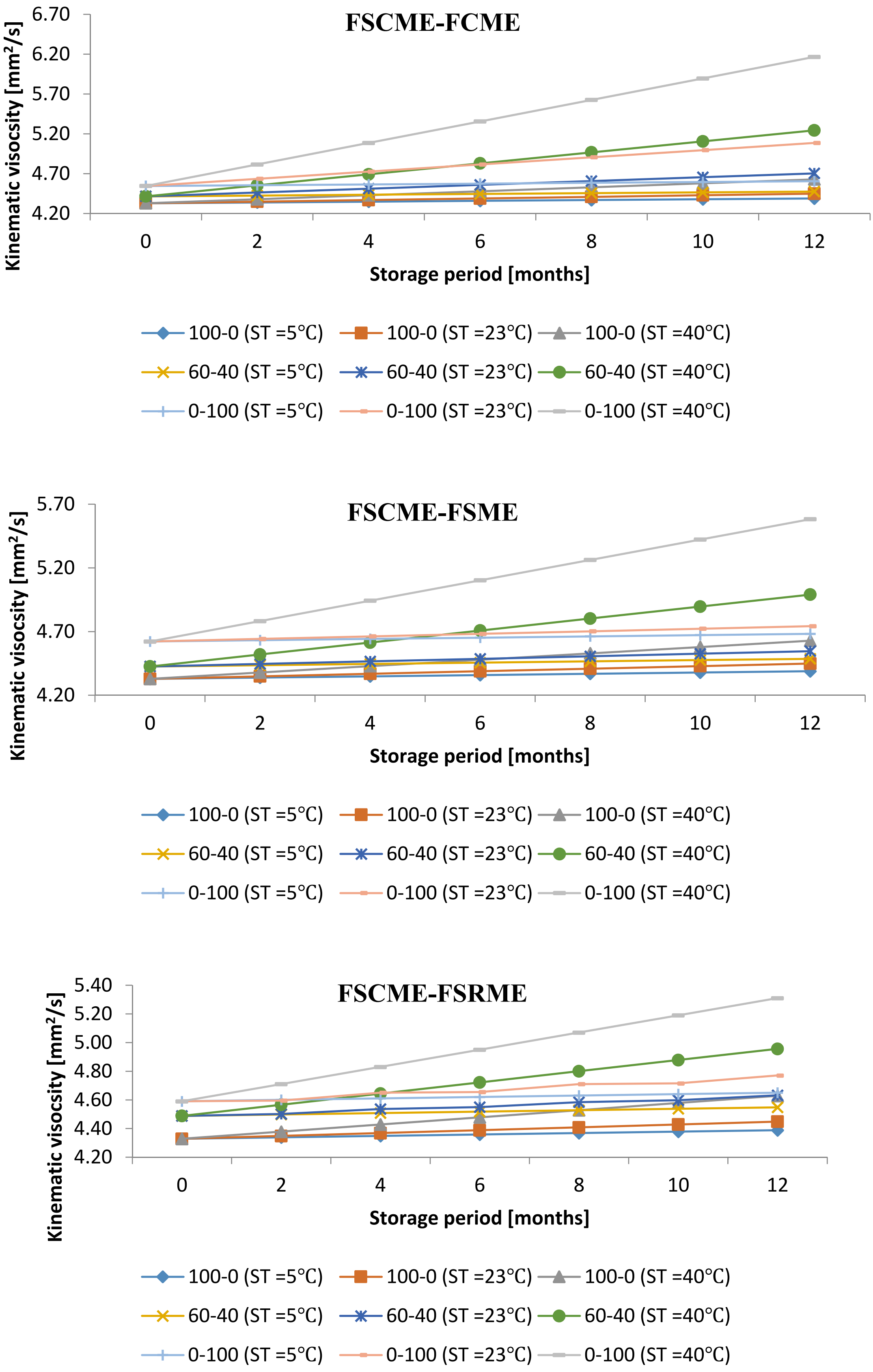

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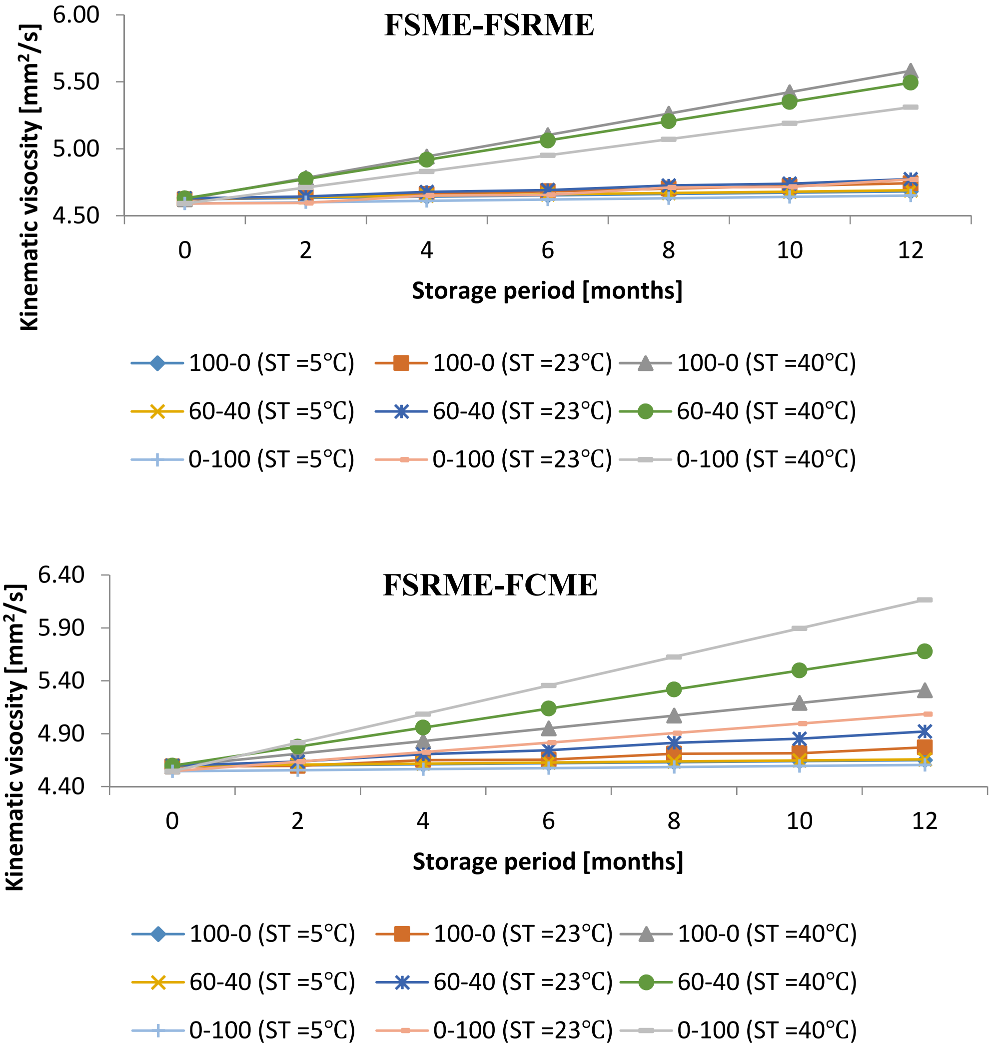
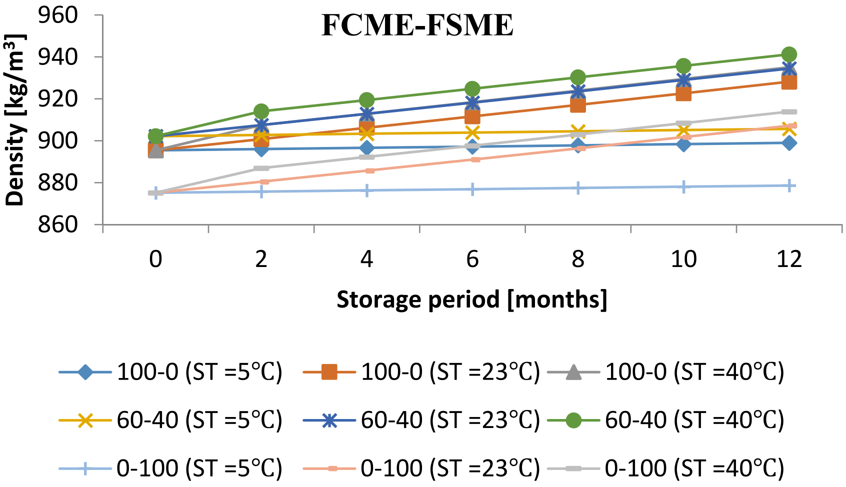


Figure 2. Kinematic viscosity results of some selected biodiesels and their blends.

3.4. Influence of Storage Period with Various Storage Conditions on Density

Table S3 summarizes the experimental results of fuel densities over several storage periods and with different conditions. The densities of some selected biodiesel and their blends, which were measured at 15 °C, are illustrated in Figure 3. The results showed that storage for 12 months resulted in a higher density for all biodiesel samples, with the increases more pronounced at higher storage temperatures. It was found that all methyl esters remained within the ranges listed in ASTM D6751 for the duration of the study at all temperatures. Furthermore, given the EN14214 standard, requiring density values at 15 °C, the density values of FCME, FSME and FSRME fulfill the requirements of the EN14214 standard (860–900 kg/m^3) for the duration of the study at ST of 5 °C, with the exception of WCME after 12 months. After extended storage (6 and 8 months) at RT, the density values of FSME and FSRME were not within the range of the EN14214 standard requiring density values at 15 °C. It was also seen that the density values of FSCME do not fit with the biodiesel standards, being in the range 860–900 kg/m^3 (EN14214 standard).



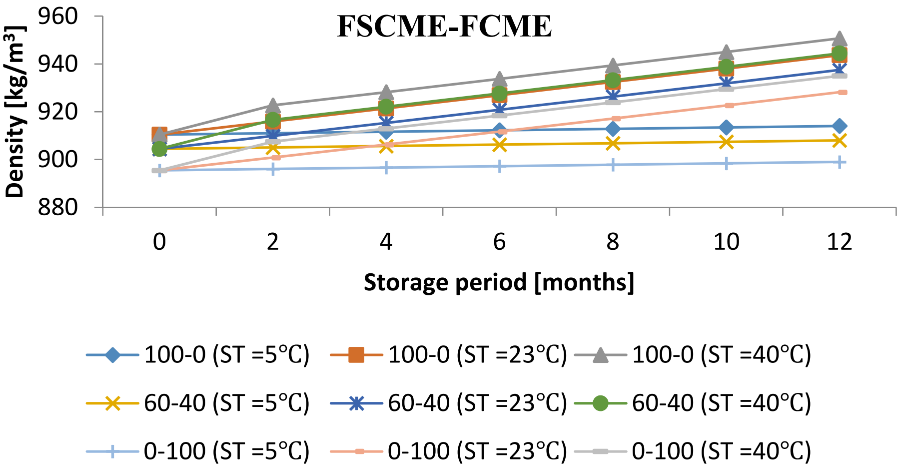


Figure 3. *Cont.*

Similarly, the increase ratio (Ir) was calculated (Equation (7)) for each biodiesel sample so as to compare the results of density for various storage conditions. It was observed that the values of Ir were greater than 1, and the value of Ir increases as the storage temperature increases, as shown in Table S3.

$$I_r = \frac{\text{Density of agiven sample at 12 months of storage}}{\text{Inital value of density of agiven sample}} \quad (7)$$

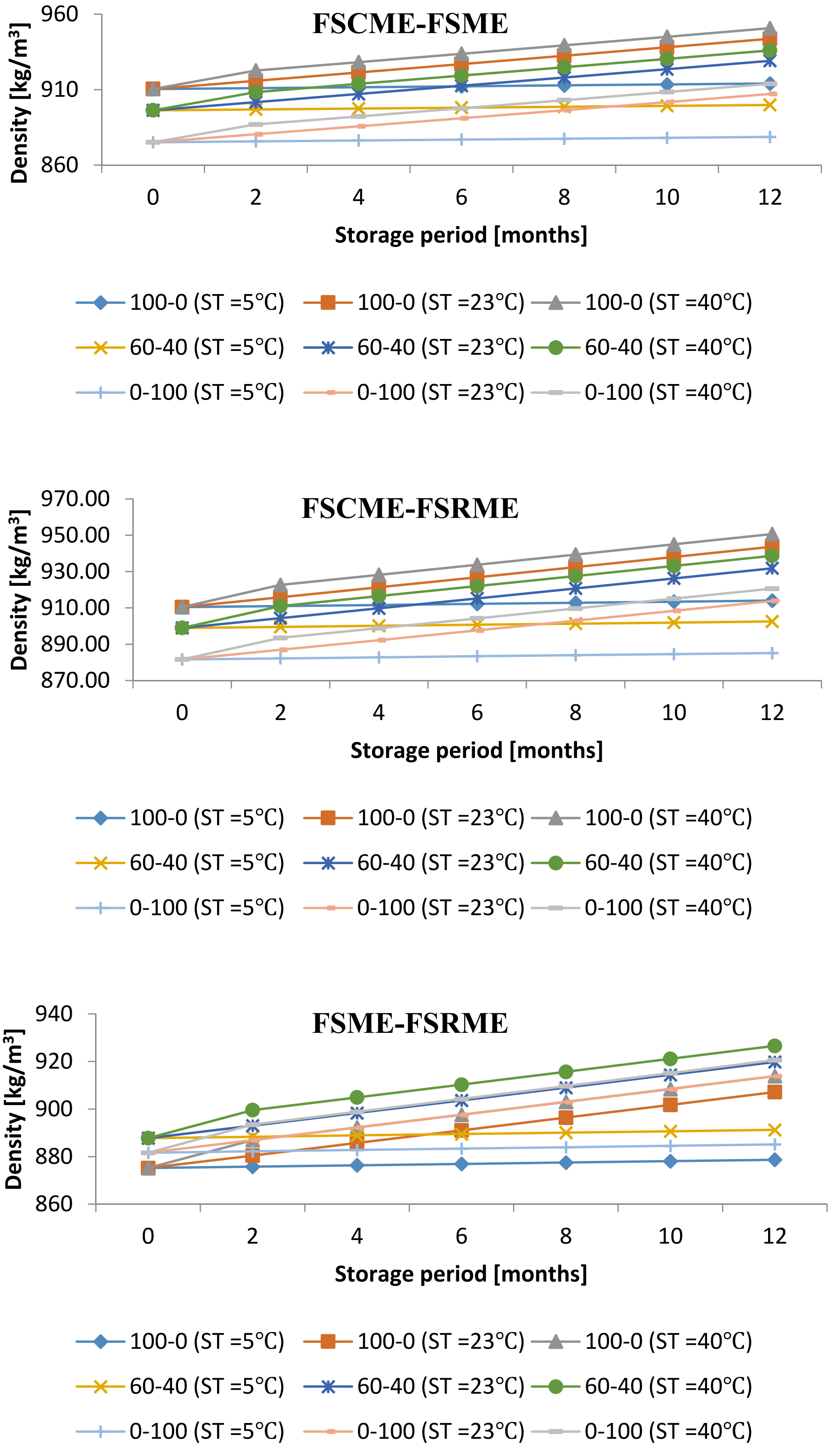


Figure 3. *Cont.*

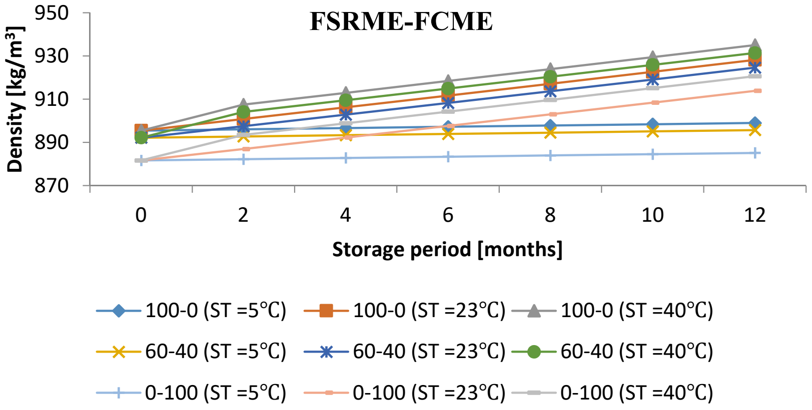


Figure 3. Density results of some selected biodiesel and their blends.

3.5. Impact of Storage Period with Various Storage Conditions on Cold Flow Properties

The cloud point (CP) and pour point (PP) values of pure biodiesel samples were measured according to ASTM D 2500 and ASTM D 97, respectively. It was found that the initial CP values of FCME, FSME, FSRME and FSCME were −2.0, 10.0, −1.2 and 7.0 °C respectively. as shown in Table 6. The corresponding values for PP were −10.0, 5.5, −6.0 and 1.6 °C, as shown in Table 6. It can be seen that FSME has the highest value of CP and PP. The considerably higher CP and PP values obtained for FSME were attributed to the presence of a higher percentage of SFAME (42.61 wt. %), as it is known that the melting point increases with decreasing double bond content. It should be noted that the concept of comparing the effects on CP or PP using an "absolute changing ratio" (ACR) is flawed for two reasons. First, absolute temperatures (in K) should be used, and this would significantly decrease the percentage changes in the temperatures. Using temperature values on the Celsius scale to calculate temperature ratios is reckless, and can lead to misleading results. Therefore, in order to show the effects of storage conditions on CP and PP results, temperature differentials in °C (ΔT = T [t = 0 months]–T [t = 12 months]) are used, and listed in Tables S4 and S5.

Table 6. Cold flow properties of unmixed and mixed biodiesels.

Blend	VF [%]	CP [°C]	PP [°C]	Blend	VF [%]	CP [°C]	PP [°C]
FCME–FSME	100–0	−2.00	−10.00	FSCME–FCME	100–0	7.00	1.60
	80–20	0.40	−6.90		80–20	5.20	−0.72
	60–40	2.80	−3.80		60–40	3.40	−3.04
	40–60	5.20	−0.70		40–60	1.60	−5.36
	20–80	7.60	2.40		20–80	−0.20	−7.68
	0–100	10.00	5.50		0–100	−2.00	−10.00
FSCME–FSRME	100–0	7.00	1.60	FSME–FSRME	100–0	10.00	5.50
	80–20	5.36	0.08		80–20	7.76	3.20
	60–40	3.72	−1.44		60–40	5.52	0.90
	40–60	2.08	−2.96		40–60	3.28	−1.40
	20–80	0.44	−4.48		20–80	1.04	−3.70
	0–100	−1.20	−6.00		0–100	−1.20	−6.00
FSRME–FCME	100–0	−1.20	−6.00	FSCME–FSME	100–0	7.00	1.60
	80–20	−1.36	−6.80		80–20	7.60	2.38
	60–40	−1.52	−7.60		60–40	8.20	3.16
	40–60	−1.68	−8.40		40–60	8.80	3.94
	20–80	−1.84	−9.20		20–80	9.40	4.72
	0–100	−2.00	−10.00		0–100	10.00	5.50

As seen in Tables S4 and S5, storage for 12 months resulted in a slight change in CP and PP values for all unmixed methyl esters, with small increases being noticed at higher storage temperatures.

The results show that the effects of storage conditions on biodiesel blends were observed in the blends mainly at the ST of RT and 40 °C, because the ΔT values ranged from −2.49 °C to 0.49 °C for the ST of RT (23 ± 1 °C), and −5.11 °C to 1 °C for the ST of 40 °C, which depended on the concentrations of biodiesel in the mixture.

3.6. Physical Properties of Unmixed Biodiesel–Gasoline Blends

As mentioned previously, the kinematic viscosities of pure biodiesel samples do not follow the standard demands for diesel fuel (ASTM D975 recommended values: 1.9–4.10 mm^2/s; EN 90 recommended values: 2.0–4.5 mm^2/s). Recent studies showed that adding fuel additives to biodiesel can improve thermo-physical properties such as viscosity, density, cold flow properties, and so on [39–41]. Furthermore, adding fuel additives to biodiesel affects the engine combustion, performance and emission characteristics of the diesel engine [40,41]. Before carrying out the analyses on the characterization of the fuel additives, including automotive gasoline, used during the storage period under various storage conditions, it was necessary to measure the properties of the biodiesel–fuel additive blends, including kinematic viscosity, in order to find the optimum blends that fulfill the diesel fuel quality standard ASTM D975 and European regulations EN 590.

Given the biodiesel standard requires that viscosity values at 40 °C be higher than 1.9 mm^2/s, biodiesel blends with gasoline content lower than 40% (volume basis) fulfill this requirement, as shown in Table 7. Additionally, as seen via comparison to the kinematic viscosity requirements contained in ASTM D6751, biodiesel blends with gasoline content between 10% and 40% (volume basis) are within the range of specification. Furthermore, when gasoline content is between 5% and 40% in the mixture, the kinematic viscosities of the samples remain within the range specification listed in EN 590. Moreover, it can be observed that the densities of biodiesel–gasoline blends decreased when the concentration percentage of gasoline increased in the mixture, as shown in Table 7. In the case of ASTM D975 (recommended values: 860–900 kg/m^3), the densities of the FCME and FSCME blend, with gasoline contents between 10% and 20%, were satisfactory according to the density specification. Furthermore, the observed results for the density of the FSME and FSRME blend with gasoline contents between 5% and 15% were within the ranges listed in the standard of ASTM D975.

Table 7. Results of kinematic viscosity in mm^2/s at 40 °C, and density in kg/m^3 at 15 °C, for unmixed biodiesel–gasoline blends for 0-month.

Volume Fraction [%]	**Kinematic Viscosity [mm^2/s]**				**Density [kg/m^3]**			
	FCME	**FSME**	**FSCME**	**FSRME**	**FCME**	**FSME**	**FSCME**	**FSRME**
100 (Pure biodiesel)	4.55	4.62	4.33	4.59	895.44	875.19	910.42	881.63
95	4.35	4.42	4.14	4.39	888.28	867.75	900.86	874.13
90	4.00	4.07	3.81	4.04	879.84	860.38	891.40	866.70
85	3.67	3.73	3.49	3.70	871.48	853.06	882.04	859.34
80	3.30	3.36	3.14	3.33	863.20	845.81	872.78	852.03
75	2.87	2.92	2.73	2.90	855.00	838.62	863.62	844.79
70	2.59	2.63	2.47	2.62	846.88	831.49	854.55	837.61
65	2.33	2.37	2.22	2.35	838.83	824.43	845.58	830.49
60	2.10	2.13	2.00	2.12	830.87	817.42	836.70	823.43
55	1.89	1.92	1.80	1.91	822.97	810.47	827.91	816.43
50	1.70	1.73	1.62	1.72	815.15	803.58	819.22	809.49
45	1.53	1.55	1.46	1.54	807.41	796.75	810.62	802.61
40	1.38	1.40	1.31	1.39	799.74	789.98	802.11	795.79
35	1.24	1.26	1.18	1.25	792.14	783.26	793.68	789.02
30	1.11	1.13	1.06	1.13	784.62	776.61	785.35	782.32
25	1.00	1.02	0.96	1.01	777.16	770.00	777.10	775.67
20	0.90	0.92	0.86	0.91	769.78	763.46	768.94	769.07
15	0.81	0.83	0.77	0.82	762.47	756.97	760.87	762.54
10	0.73	0.74	0.70	0.74	755.22	750.54	752.88	756.06
5	0.66	0.67	0.63	0.66	748.05	744.16	744.98	749.63
0 (Pure fuel additive)	0.59	0.59	0.59	0.59	740.94	740.94	740.94	740.94

3.6.1. Influence of Storage Period with Various Storage Condition on Kinematic Viscosity

Based on the findings (Section 3.6), samples of biodiesel–gasoline blends were within the ranges listed in ASTM D975. Biodiesel BG90 contained 90% biodiesel and 10% gasoline. Similarly, BG85, BG80, BG75, BG70, BG65 and BG60 contain 85%, 80%, 75%, 70%, 65% and 60% biodiesel by volume, respectively. Table S6 presents the experimental results of the kinematic viscosities of the selected samples over 12 months, under various storage conditions (5 °C, RT, 40 °C). It can be noticed that the kinematic viscosities did not change significantly at lower storage temperatures. In addition, all the samples remained within the ranges listed in ASTM D975 at an ST of 5 °C, with the exception of FSME (BG90) and FSRME (BG90) after 8 and 12 months, respectively. Additionally, the kinematic viscosities of other biodiesel samples (BG85, BG80, BG75, BG70, BG65 and BG60) were satisfactory, according to the kinematic viscosity specifications listed in ASTM D975 for the duration of the study at all storage temperatures.

3.6.2. Influence of Storage Period with Various Storage Condition on Cold Flow Properties

Moreover, the low temperature properties of the selected blends were measured through determination of the CP and PP. Based on the findings, seven biodiesel–gasoline blends remained within the range of viscosity specification as listed in ASTM D975, i.e., the biodiesel component in each blend was 90%, 85%, 80%, 75%, 70%, 65% and 60% (*v*/*v*), mixed with gasoline. The designation of BGx is used by this paper in reference to these fuel blends, where x means weight percentage of biodiesel in blends of gasoline. For example, BG90 refers to a blend of 90% biodiesel and 10% gasoline. The fuel samples were analyzed over various storage periods and conditions after blending with gasoline. Figure 4 shows that the high CP and PP values of biodiesel samples were reduced after blending with gasolines, which has low CP and PP values. For pure biodiesel samples (BG100), the CP values were found to be 7.0 10.0, −2.0 and −1.2 °C for FSCME, FSME, FCME and FSRME, respectively, and the values of PP were found to be 1.6, 5.5, −10.0 and −6.0 °C for FSCME, FSME, FCME and FSRME, respectively. The blend of BG60 had the lowest CP and PP as compared to other blends due to the low CP and PP of gasoline. Additionally, Figures S5–S8 illustrate the effect of storage periods and conditions on the cold flow properties of the selected samples. According to the gasoline standard, gasoline fuel starts evaporating at 70 °C; therefore, as storage temperature increased, the CP and PP of the samples became closer to the cold flow properties of pure biodiesel, especially after 12 months.

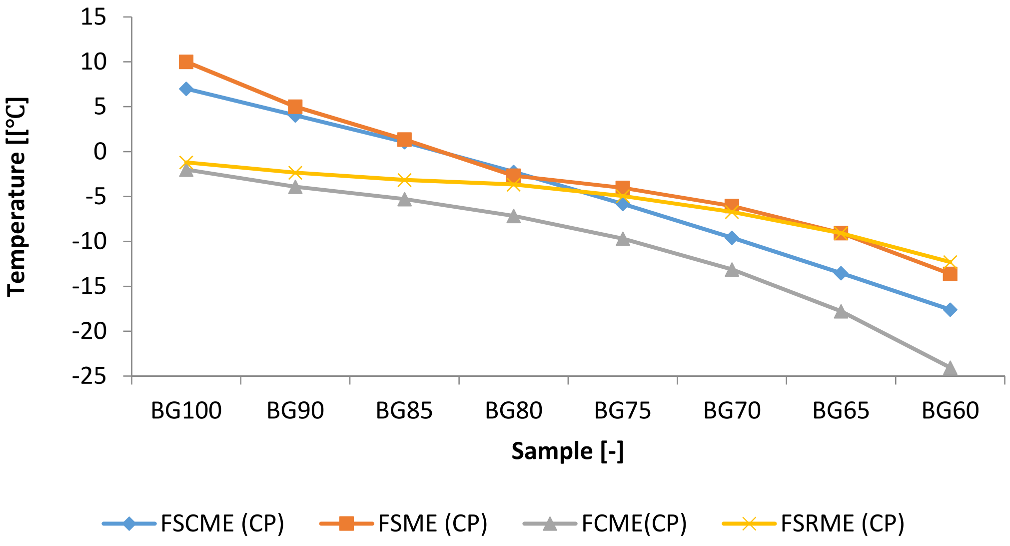


Figure 4. *Cont.*

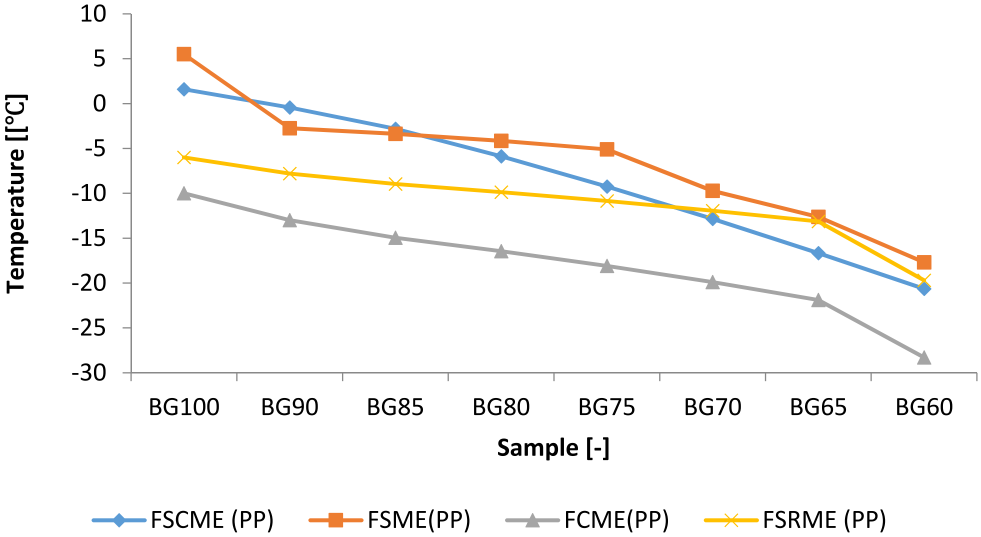


Figure 4. Cold flow properties of biodiesel–gasoline blends for 0-month.

3.7. Physical Properties of Triple Blends

Based on the results of Sections 3.1–3.6, the investigation of the experimental results showed that:

- The kinematic viscosities of all blends are above the limit specification of ASTM D975, while some samples with various concentrations of FSCME fulfill the European regulations EN 590.
- Based on the oxidation stability specification listed in EN 14214:2014, the minimum specified limit of 8 h is required to ensure adequate biodiesel stability during a typical 6-month fuel consumption timeframe [32,37]. The results indicated that out of 26 samples, 10 samples had an oxidation stability above 10 h for 0-month. These samples are mixed with various percentages of FSCME. It can be noted that storage conditions strongly influence the stability of biodiesel [31,32]. According to Plessis et al. [42], biodiesel remains stable if stored at 20 °C in closed containers. The results showed that when the sample is stored at 5 °C, all these samples remain stable. It was also observed that when the concentration amount of FSCME decreased, the samples after 2 or 4 months of storage at RT were no longer above the minimum oxidative stability specification.
- The cold flow results showed that these samples have poor cold flow properties. It was found that CP and PP values were within the ranges of −0.2–8.80 °C and −7.68–3.94 °C.

In general, the kinematic viscosity, density and cold flow properties of the fuel are the most important rheological properties that affect the engine performance. In order to use biodiesel in transport arena, it must fulfill the standard requirements (ASTM D975 and EN 590). Thus, the aim of this study was to improve the kinematic viscosity, density and the cold flow properties of these samples by mixing them with various percentages of gasoline. Consequently, their samples were mixed with various concentration amounts of gasoline (15% and 20%) so as to improve the properties of the biodiesel, including kinematic viscosity, density and cold flow properties. Data from Tables 8 and 9 show that the viscosity and density values of biodiesel–gasoline fuel blends are in accordance with the standard demand for diesel fuel (ASTM D975 and EN 90). Furthermore, Tables 10 and 11 show that high the CP and PP values of biodiesel blends were reduced after blending with the gasoline, which has low CP and PP. Based on the results of Section 3.6.1, it was found that the experimental results regarding the kinematic viscosity of all blends were satisfactory according to the specifications listed in ASTM D975 and EN 590 when the samples were stored at 5 °C. In fact, ambient temperature is considered an essential factor that affects the degradation of fuel, and the degradation of fuel depends on humidity conditions and ambient temperature. Furthermore, based on the results obtained by Reference [42], it was concluded that biodiesel remains stable if stored at 20 °C in closed containers.

Therefore, the impact of storage period on the properties of triple blends is investigated for a storage temperature of RT (23 ± 1 °C), as shown in Tables 8–11. The results indicate that the properties of the fuel samples increase with time. The blending of biodiesel is a simple but effective method to improve the low-temperature flow properties of biodiesel.

Table 8. Influence of storage period on kinematic viscosity in mm^2/s measured at 40 °C.

Blend	**VF [%]**	**Storage Period [month]**						
		0	**2**	**4**	**6**	**8**	**10**	**12**
EFSCME–FSRME (80–20)–Gasoline	100–0	4.36	4.37	4.40	4.42	4.45	4.46	4.49
	85–15	3.52	3.59	3.66	3.73	3.81	3.88	3.96
	80–20	2.55	2.60	2.66	2.71	2.76	2.82	2.87
EFSCME–FSRME (60–40)–Gasoline	100–0	4.49	4.50	4.54	4.55	4.58	4.60	4.63
	85–15	3.62	3.70	3.79	3.88	3.97	4.06	4.15
	80–20	2.63	2.68	2.73	2.79	2.85	2.90	2.96
EFSCME–FSRME (40–60)–Gasoline	100–0	4.51	4.52	4.56	4.57	4.61	4.62	4.66
	85–15	3.63	3.73	3.82	3.91	4.01	4.11	4.22
	80–20	2.64	2.70	2.76	2.83	2.89	2.96	3.02
FSCME-FCME (80–20)–Gasoline	100–0	4.37	4.41	4.44	4.47	4.51	4.54	4.58
	85–15	3.53	3.58	3.63	3.69	3.74	3.80	3.86
	80–20	2.56	2.61	2.66	2.71	2.77	2.82	2.88
FSCME-FCME (60–40)–Gasoline	100–0	4.42	4.46	4.51	4.56	4.61	4.66	4.70
	85–15	3.56	3.62	3.67	3.72	3.78	3.84	3.89
	80–20	2.59	2.64	2.69	2.74	2.79	2.85	2.90
FSCME-FCME (40–60)–Gasoline	100–0	4.59	4.52	4.58	4.64	4.71	4.77	4.83
	85–15	3.70	3.79	3.89	3.99	4.09	4.19	4.29
	80–20	2.69	2.75	2.81	2.88	2.94	3.01	3.08
FSCME-FCME (20–80)–Gasoline	100–0	4.57	4.65	4.73	4.80	4.88	4.95	5.03
	85–15	3.69	3.77	3.86	3.95	4.04	4.13	4.23
	80–20	2.68	2.73	2.79	2.84	2.90	2.96	3.02
FSCME–FSME (80–20)–Gasoline	100–0	4.37	4.39	4.41	4.43	4.45	4.47	4.49
	85–15	3.52	3.61	3.70	3.79	3.89	3.99	4.09
	80–20	2.56	2.62	2.68	2.74	2.80	2.87	2.93
FSCME–FSME (60–40)–Gasoline	100–0	4.43	4.45	4.47	4.49	4.51	4.53	4.55
	85–15	3.57	3.64	3.71	3.79	3.86	3.94	4.02
	80–20	2.59	2.64	2.69	2.75	2.80	2.85	2.91
FSCME–FSME (40–60)–Gasoline	100–0	4.48	4.50	4.52	4.54	4.56	4.58	4.60
	85–15	3.61	3.70	3.78	3.87	3.96	4.05	4.14
	80–20	2.62	2.68	2.73	2.78	2.84	2.90	2.95

Table 9. Influence of storage period on density in kg/m^3 measured at 15 °C.

Blend	**VF [%]**	**Storage Period [Month]**						
		0	**2**	**4**	**6**	**8**	**10**	**12**
EFSCME–FSRME (80–20)–Gasoline	100–0	904.64	910.07	915.53	921.02	926.55	932.11	937.70
	85–15	881.77	889.70	898.60	907.58	916.66	921.24	930.46
	80–20	852.17	859.84	868.43	877.12	885.89	890.32	899.22
EFSCME–FSRME (60–40)–Gasoline	100–0	898.96	904.35	909.78	915.24	920.73	926.25	931.81
	85–15	876.23	884.11	892.96	901.89	910.90	915.46	924.61
	80–20	846.81	854.44	862.98	871.61	880.33	884.73	893.58

Table 9. *Cont.*

Blend	VF [%]	Storage Period [Month]						
		0	**2**	**4**	**6**	**8**	**10**	**12**
EFSCME–FSRME (40–60)–Gasoline	100–0	893.16	898.52	903.91	909.34	914.79	920.28	925.80
	85–15	870.58	878.42	887.20	896.07	905.03	909.56	918.65
	80–20	841.36	848.93	857.42	865.99	874.65	879.03	887.82
FSCME-FCME (80–20)–Gasoline	100–0	907.42	912.87	918.35	923.86	929.40	934.98	940.59
	85–15	884.48	892.44	901.37	910.38	919.48	924.08	933.32
	80–20	854.79	862.48	871.11	879.82	888.62	893.06	901.99
FSCME-FCME (60–40)–Gasoline	100–0	904.43	909.86	915.31	920.81	926.33	931.89	937.48
	85–15	881.56	889.50	898.39	907.37	916.45	921.03	930.24
	80–20	851.97	859.64	868.23	876.91	885.68	890.11	899.01
FSCME-FCME (40–60)–Gasoline	100–0	912.93	918.34	923.78	929.26	934.76	940.30	945.88
	85–15	889.85	897.86	906.84	915.91	925.07	929.69	938.99
	80–20	859.98	867.72	876.40	885.16	894.01	898.48	907.47
FSCME-FCME (20–80)–Gasoline	100–0	903.44	908.83	914.25	919.71	925.20	930.72	936.27
	85–15	880.60	888.52	897.41	906.38	915.44	920.02	929.22
	80–20	851.03	858.69	867.28	875.95	884.71	889.14	898.03
FSCME–FSME (80–20)–Gasoline	100–0	903.37	908.79	914.25	919.73	925.25	930.80	936.39
	85–15	880.53	888.46	897.34	906.32	915.38	919.96	929.16
	80–20	850.97	858.63	867.22	875.89	884.65	889.07	897.97
FSCME–FSME (60–40)–Gasoline	100–0	896.33	901.71	907.12	912.56	918.03	923.54	929.08
	85–15	873.67	881.53	890.34	899.25	908.24	912.78	921.91
	80–20	844.34	851.94	860.46	869.06	877.75	882.14	890.96
FSCME–FSME (40–60)–Gasoline	100–0	889.28	894.62	899.99	905.39	910.82	916.28	921.78
	85–15	866.80	874.60	883.34	892.18	901.10	905.61	914.66
	80–20	837.70	845.24	853.69	862.23	870.85	875.21	883.96

Table 10. Influence of storage period on Cloud Point in °C.

Blend	VF [%]	Storage Period [Month]						
		0	**2**	**4**	**6**	**8**	**10**	**12**
EFSCME–FSRME (80–20)–Gasoline	100–0	5.20	5.41	5.62	5.85	6.08	6.33	6.58
	85–15	−1.04	−1.0	−1.0	−0.9	−0.9	−0.8	−0.8
	80–20	−3.12	−3.0	−2.9	−2.8	−2.6	−2.5	−2.4
EFSCME–FSRME (60–40)–Gasoline	100–0	3.40	3.54	3.68	3.82	3.98	4.14	4.30
	85–15	−0.68	−0.7	−0.6	−0.6	−0.6	−0.6	−0.5
	80–20	−2.04	−2.0	−1.9	−1.8	−1.7	−1.7	−1.6
EFSCME–FSRME (40–60)–Gasoline	100–0	1.60	1.66	1.73	1.80	1.87	1.95	2.02
	85–15	−0.32	−0.3	−0.3	−0.3	−0.3	−0.3	−0.2
	80–20	−0.96	−0.9	−0.9	−0.8	−0.8	−0.8	−0.8
FSCME–FCME (80–20)–Gasoline	100–0	5.20	5.41	5.62	5.85	6.08	6.33	6.58
	85–15	−1.04	−1.0	−1.0	−0.9	−0.9	−0.8	−0.8
	80–20	−3.12	−3.0	−2.9	−2.8	−2.6	−2.5	−2.4
FSCME–FCME (60–40)–Gasoline	100–0	3.40	3.54	3.68	3.82	3.98	4.14	4.30
	85–15	−0.68	−0.7	−0.6	−0.6	−0.6	−0.6	−0.5
	80–20	−2.04	−2.0	−1.9	−1.8	−1.7	−1.7	−1.6

Table 10. *Cont.*

Blend	**VF [%]**	**Storage Period [Month]**						
		0	**2**	**4**	**6**	**8**	**10**	**12**
FSCME–FCME (40–60)–Gasoline	100–0	1.60	1.66	1.73	1.80	1.87	1.95	2.02
	85–15	−0.32	−0.3	−0.3	−0.3	−0.3	−0.3	−0.2
	80–20	−0.96	−0.9	−0.9	−0.8	−0.8	−0.8	−0.8
FSCME–FCME (20–80)–Gasoline	100–0	−0.20	−0.21	−0.22	−0.22	−0.23	−0.24	−0.25
	85–15	−0.44	−0.4	−0.4	−0.4	−0.4	−0.4	−0.3
	80–20	−0.52	−0.5	−0.5	−0.5	−0.4	−0.4	−0.4
FSCME–FSME (80–20)–Gasoline	100–0	7.60	7.90	8.22	8.55	8.89	9.25	9.62
	85–15	−1.52	−1.5	−1.4	−1.3	−1.3	−1.2	−1.2
	80–20	−4.56	−4.4	−4.2	−4.0	−3.9	−3.7	−3.6
FSCME–FSME (60–40)–Gasoline	100–0	8.20	8.53	8.87	9.22	9.59	9.98	10.38
	85–15	−1.64	−1.6	−1.5	−1.5	−1.4	−1.3	−1.3
	80–20	−4.92	−4.7	−4.5	−4.4	−4.2	−4.0	−3.9
FSCME–FSME (40–60)–Gasoline	100–0	8.80	9.15	9.52	9.90	10.29	10.71	11.13
	85–15	−1.76	−1.7	−1.6	−1.6	−1.5	−1.4	−1.3
	80–20	−5.28	−5.1	−4.9	−4.7	−4.5	−4.3	−4.1

Table 11. Influence of storage period on Pour Point in °C.

Blend	**VF [%]**	**Storage Period [month]**						
		0	**2**	**4**	**6**	**8**	**10**	**12**
EFSCME–FSRME (80–20)–Gasoline	100–0	0.08	0.08	0.09	0.09	0.09	0.10	0.10
	85–15	−1.07	−1.0	−0.9	−0.9	−0.8	−0.8	−0.7
	80–20	−1.36	−1.3	−1.2	−1.1	−1.0	−1.0	−0.9
EFSCME–FSRME (60–40)–Gasoline	100–0	−1.44	−1.38	−1.33	−1.27	−1.22	−1.17	−1.13
	85–15	−3.74	−3.6	−3.5	−3.3	−3.2	−3.1	−2.9
	80–20	−4.32	−4.1	−4.0	−3.8	−3.7	−3.5	−3.4
EFSCME–FSRME (40–60)–Gasoline	100–0	−2.96	−2.84	−2.73	−2.62	−2.51	−2.41	−2.32
	85–15	−7.70	−7.4	−7.1	−6.8	−6.5	−6.3	−5.9
	80–20	−8.88	−8.5	−8.2	−7.9	−7.5	−7.2	−7.0
FSCME–FCME (80–20)–Gasoline	100–0	−0.72	−0.69	−0.66	−0.64	−0.61	−0.59	−0.56
	85–15	−1.87	−1.8	−1.7	−1.7	−1.6	−1.5	−1.4
	80–20	−2.16	−2.1	−2.0	−1.9	−1.8	−1.8	−1.7
FSCME–FCME (60–40)–Gasoline	100–0	−3.04	−2.92	−2.80	−2.69	−2.58	−2.48	−2.38
	85–15	−7.90	−7.6	−7.3	−7.0	−6.7	−6.4	−6.1
	80–20	−9.12	−8.8	−8.4	−8.1	−7.7	−7.4	−7.1
FSCME–FCME (40–60)–Gasoline	100–0	−5.36	−5.15	−4.94	−4.74	−4.55	−4.37	−4.20
	85–15	−13.94	−13.4	−12.8	−12.3	−11.8	−11.4	−10.7
	80–20	−16.08	−15.4	−14.8	−14.2	−13.7	−13.1	−12.6
FSCME–FCME (20–80)–Gasoline	100–0	−7.68	−7.37	−7.08	−6.79	−6.52	−6.26	−6.01
	85–15	−19.97	−19.2	−18.4	−17.7	−17.0	−16.3	−15.3
	80–20	−23.04	−22.1	−21.2	−20.4	−19.6	−18.8	−18.0
FSCME–FSME (80–20)–Gasoline	100–0	2.38	2.48	2.57	2.68	2.78	2.90	3.01
	85–15	−1.43	−1.4	−1.3	−1.3	−1.2	−1.2	−1.1
	80–20	−2.38	−2.3	−2.2	−2.1	−2.0	−1.9	−1.9

Table 11. *Cont.*

Blend	VF [%]	Storage Period [month]						
		0	2	4	6	8	10	12
FSCME–FSME (60–40)–Gasoline	100–0	3.16	3.29	3.42	3.55	3.70	3.84	4.00
	85–15	−1.90	−1.8	−1.7	−1.7	−1.6	−1.5	−1.5
	80–20	−3.16	−3.0	−2.9	−2.8	−2.7	−2.6	−2.5
FSCME–FSME (40–60)–Gasoline	100–0	3.94	4.10	4.26	4.43	4.61	4.79	4.99
	85–15	−2.36	−2.3	−2.2	−2.1	−2.0	−1.9	−1.8
	80–20	−3.94	−3.8	−3.6	−3.5	−3.3	−3.2	−3.1

4. Conclusions

This study supported the assertion that raw material composition largely influences the properties of biodiesel, including oxidation stability, viscosity, density and cold flow properties. The cold flow properties of high-temperature biodiesels were improved by blending them with low-temperature biodiesels, or with additive fuel such as automobile gasoline. Special attention was given to blends formulated with WSCME. Adding this to unmixed biodiesel at various concentration amounts was effective in increasing the oxidative stability of FSME, FCME and FSRME. Additionally, blending the FSCME–biodiesel with gasoline reduced the kinematic viscosity and density down to the limit values of the viscosity and density specifications, listed in the diesel standards. The experimental results demonstrated that the properties of blends, including the kinematic viscosity, density and cold flow properties, increased with time, and oxidative stability was significantly reduced upon extended storage, with these effects more pronounced at high storage temperatures.

Supplementary Materials: The following are available online at http://www.mdpi.com/1996-1073/13/16/4111/s1, Figure S1: Kinematic viscosity and dynamic viscosity of fresh biodiesel and their blends, Figure S2: Measured kinematic viscosities of all biodiesel and their blends, Figure S3: Measured densities of all biodiesel and their blends, Figure S4: Kinematic viscosity of some selected blends at various testing temperature: (a) FCME-FSME, (b) FSRME-FCME, (c) FSCME-FCME and (d) FSME-FSRME, Figure S5: Cold flow properties of FCME-gasoline blends for various storage periods and conditions, Figure S6: Cold flow properties of FSME-gasoline blends for various storage periods and conditions, Figure S7: Cold flow properties of FSCME-gasoline blends for various storage periods and conditions, Figure S8: Cold flow properties of FSRME-gasoline blends for various storage periods and conditions, Table S1: Influence of extended storage on oxidative stability in h for all pure biodiesel samples, Table S2: Influence of storage period and conditions on kinematic viscosity in mm2/s of pure biodiesel at 40°C, Table S3: Influence of storage period and conditions on density in kg/m^3 of pure biodiesel at 15 °C, Table S4: Influenced of storage period and conditions on cloud Point in °C, Table S5: Influenced of storage period and conditions on Pour Point in °C, Table S6: Influence of storage period and conditions on kinematic viscosity in mm2/s of biodiesel-gasoline blends at 40°C.

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