

Article

Properties of Components of Renewable Motor Fuel Based on Plant Oils and Assessment of Their Compatibility with Traditional Fuels

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Abstract: The growing demand for sustainable and environmentally friendly fuels and the increasing need to diversify energy sources have stimulated significant research in the field of renewable motor fuels. Despite the progress made, there is still a need to expand the feedstocks, optimize technological pathways, and, in particular, conduct comprehensive studies of the compatibility of renewable components with traditional fuels. In light of the above, the authors propose optimizing the properties of renewable fuels by using new vegetable oils and alcohols for their synthesis. The work is focused on studying the basic physical–chemical properties of fatty acid esters and assessing the possibility of using them as renewable components of motor fuels. Renewable components were obtained via the esterification of selected plant oils (rapeseed oil, camelina oil, palm kernel oil, and coconut oil) with different alcohols (ethanol and isobutanol) with further vacuum distillation of esters. The influence of the structure and composition of renewable components on their physical–chemical properties was studied and substantiated. It shows how the carbon number distribution and double bonds in fatty acid radicals influence the properties of renewable components. The paper shows the impact of the type and structure of alcohol used for esterification on the properties of studied products. The regularities in the change in properties of renewable components depending on the composition of oils and alcohols are explained and substantiated from the point of view of physical chemistry and the basics of forces of intermolecular interactions. Renewable components were compared to the properties of conventional motor fuels (diesel fuel and jet fuel). Based on the level of component compatibility with petroleum fuels, recommendations for replacing or blending petroleum fuels with renewable components were proposed.

Keywords: fatty acid esters; plant oil; renewable fuel; diesel fuel; jet fuel; sustainable fuel; physical–chemical properties; compatibility



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1. Introduction

The modern world is in a new energy era marked by increased demand for fuel and energy resources. Despite fluctuations in demand and oil prices, the rising trend of fuel and energy consumption is expected to persist in the coming decades. Simultaneously,

societal development trends require improved energy efficiency, timely solutions for fuel shortage, reduced environmental impact, and modernization of the energy sector to meet the needs of the 21st century.

Developing renewable, environmentally safe, and economically viable energy sources is one of the priority tasks nowadays [1–3]. One key solution is transitioning to renewable and sustainable fuels for motor and air transport (i.e., biodiesel fuel, sustainable aviation fuel).

The work by [4] compares various sustainable vehicle technologies, highlighting the potential of biofuel-powered vehicles in reducing carbon emissions. Although electric and fuel cell vehicles are often seen as the future of sustainable transport, it confirms that, currently, biofuels offer a viable and immediate solution, especially for sectors where electrification is challenging, such as aviation and heavy-duty transport. Integrating biofuels into the current energy sector is a solution to achieve near-term decarbonization goals. Similarly, the works by [5,6] highlight the potential of biofuels to reduce greenhouse gas emissions and enhance energy security significantly. However, it requires developing a comprehensive framework that includes technological advancements, policy support, and public acceptance to ensure the successful adoption of biofuels. This view is also supported by other work [7] that provides an in-depth evaluation of the current biofuel technologies and policies. The work concludes that while biofuels have significant potential to contribute to sustainable transport, their success largely depends on supportive policies and technological advancements. The authors of [8], as well as others [5,8–10], have comprehensively evaluated the environmental impacts of biofuels, showing that first-generation biofuels offer limited GHG reductions. In contrast, second-generation biofuels have better potential to enhance sustainability. The following work [11] presents the latest developments in biofuel production. The authors focus on using organic matter from aquatic environments and soil for renewable energy production, emphasizing the potential of waste materials. Different biofuels such as methane, hydrogen, ethanol, bioelectricity, algal diesel, butanol, and various production techniques, including thermal and biochemical methods, are presented and analyzed for converting waste into bioenergy.

Biofuels currently in use include biodiesel, which is traditionally produced from vegetable oils or animal fats through transesterification and used in conventional diesel engines; bioethanol, received via fermentation of sugar and starch components of plant materials, primarily corn and sugarcane and used for blending with petroleum gasoline; biogas that is generated through the anaerobic digestion of organic waste and applied for heating, electricity and sometimes as fuel for vehicles; biokerosene or sustainable aviation fuel that is produced from various organic feedstock and used in aircraft jet engines [12]. Recent research [13,14] also informs us about new technologies of advanced biofuel production that are actively developing. These fuels are expected to be derived from non-food biomass like agricultural residues, forestry waste, and algae.

The most popular feedstock for biodiesel production are various plant oils like rapeseed, soybean, palm, camelina oil, etc., animal fats like tallow, lard, and chicken or beef fat, and meat industry by-products and waste oils like used cooking oils [13,15]. These feedstock and processing technologies are well-known and widely used in different countries. The choice of feedstock is determined by its availability in certain regions [6]. The use of microalgae is a comparatively new and promising approach for biofuel production. However, as mentioned in previous studies [16,17], it faces many challenges related to high production costs, cultivation and harvesting, low lipid yields, and potential environmental impacts.

Considering the issue of biokerosene production, the industry relies on all the same types of feedstock for biodiesel production, as well as some others, such as lignocellulosic materials, waste biomass, municipal waste, and others [13,18]. However, unlike biodiesel, biokerosene or aviation biofuel production technologies are more complex and advanced and require a deeper degree of feedstock processing and refining of final products [6,19].

Extensive research on first-generation biofuels, primarily derived from food crops such as corn and rapeseed oil, has revealed several environmental and technological limitations associated with these biofuels. They include competition with the food supply, low potential to mitigate GHG emissions, suboptimal fuel properties, limited compatibility with transport operation materials, and a short storage period. Considering the relevant simplicity of production technology, the authors consider the possibility of optimizing the properties of biofuels by using new vegetable oils and alcohols for their synthesis.

The composition of the oils used as feedstock directly determines the properties of biofuels and, as a result, causes certain shortcomings in their quality, in particular, low chemical stability, unsatisfactory low-temperature properties, increased viscosity, and some others [11,12]. Based on the above, it can be expected that the selection of oils of a particular composition can improve biofuels' physical–chemical and operational properties. For this purpose, oils such as coconut, palm, Babassu, and similar may be considered. Due to the high content of saturated fatty acids, they can contribute to the improved stability of biofuels [11].

Another promising area of research may be the selection of alcohols for the synthesis of biofuels. Methanol is the most common and widely used alcohol in biodiesel production, mainly due to its effectiveness in transesterification. However, several disadvantages are associated with its use: the significant health risks because of its high toxicity, its high level of corrosiveness, it is produced from non-renewable feedstock (natural gas), and it results in biodiesel with low energy content [12,15]. Higher alcohols (ethanol, propanol, butanol, etc.) may be considered to replace methanol. Even though the efficiency of transesterification is reduced with the rising carbon number in alcohols, they can positively affect fuel properties. Ethanol and mainly butanol can be produced from various biomass sources, including agricultural residues and non-food crops; butanol and isobutanol can also be produced via microbiological fermentation, resulting in lower energy consumption and reduced GHG emissions. The use of alcohols with two or more carbon atoms can result in a higher energy content of biofuel than methanol. The use of isomerized alcohol can improve the fluidity and low-temperature properties of biofuels.

This study focuses on selecting plant oils with the required initial properties and alcohols with more carbon atoms to obtain renewable fuel components with optimized properties. This approach not only aims to enhance biofuels' physical–chemical and operational properties but also ensures the sustainability of their production process. The practical result of the work will be the ability to increase the share of renewable components in blended biofuels or ensure the complete replacement of petroleum fuel with biofuels while maintaining the desired performance properties.

Ukraine, a country with a highly developed agricultural sector, mild climatic conditions, and large areas of fertile soils, is considering intensifying the production of renewable fuels to satisfy its internal energy needs. Developing renewable or sustainable fuels will provide transport and energy safety in Ukraine, especially in the post-war period. Expanding feedstock for fuel production will help increase resource and energy conservation and reduce the state's dependence on oil imports, which will be one of the priorities for restoring the state's economy and energy sector in the post-war period. It will also contribute to the greening of the transport industry.

This work aims to assess the innovative potential of producing biofuels from non-traditional vegetable oils and higher alcohols, focusing on their physical–chemical properties and compatibility with conventional motor fuels. The main *objective* of the work is to advance the understanding of how the compositions of selected plant oils and alcohols can optimize fuel properties. Assessing the compatibility of these renewable components and traditional fuels will contribute to developing more efficient and sustainable biofuels, addressing the limitations of first-generation biofuels.

2. Materials and Methods

This study used four types of plant oils (rapeseed oil, camelina oil, palm kernel oil, and coconut oil) to produce renewable fuel components. Fuel components were obtained using the oil esterification method at the Department of Catalytic Synthesis of the V. Kukhar Institute of Bioorganic Chemistry and Petrochemistry of the National Academy of Sciences of Ukraine. Rapeseed oil and camelina oil esters were synthesized during previous studies using ethyl alcohol, as described in [20]. Palm kernel and coconut oil esters were synthesized using ethyl and isobutyl alcohol. The following reagents were used for synthesis: unrefined camelina oil and unrefined rapeseed oil, both produced by VEDALAN LLC (Ukraine); unrefined cold-pressed palm kernel oil and unrefined cold-pressed coconut oil, both originating from Malaysia; ethyl alcohol technical (Ukraine), isobutyl alcohol technical (China), and potassium hydroxide technical (Korea).

Ethyl esters of coconut and palm kernel oils were synthesized in a conical flask with mechanical stirring at an ambient temperature using an ethanolic solution of potassium ethylate by direct transesterification of oil triglycerides with ethyl alcohol. The duration of the reaction was 30–45 min. After settling the reaction mixture, the lower glycerol-enriched layer and the upper ester-enriched layer were separated. The principal flowchart describing the synthesis of ethyl esters is given in Figure 1.

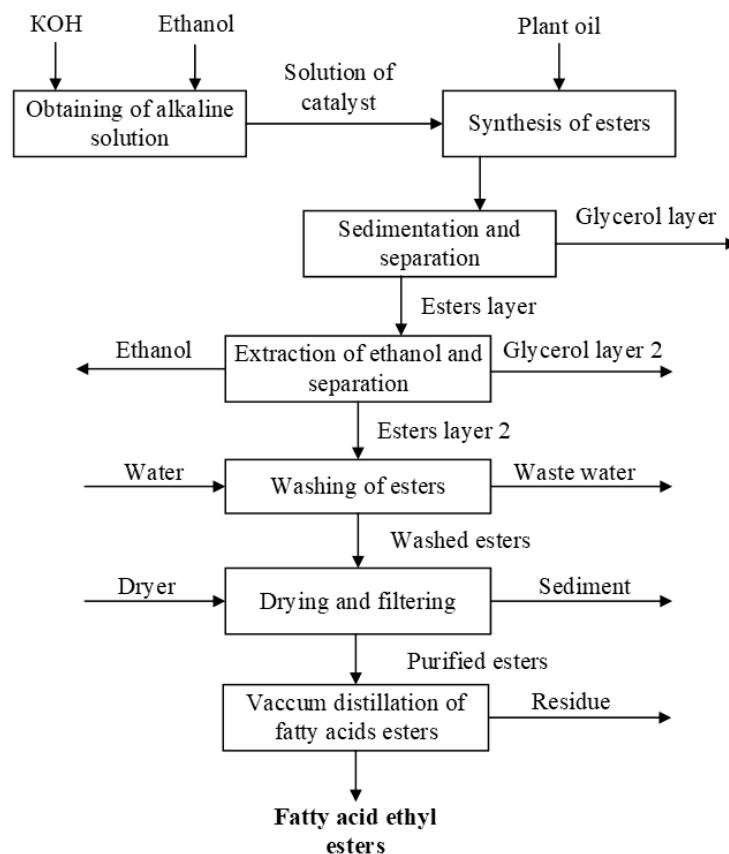


Figure 1. Flowchart of synthesis of ethyl esters.

Isobutyl esters of coconut oil and palm kernel oils were synthesized via the esterification of fatty acids of the corresponding oils. First, the oil was saponified with a solution of KOH in ethyl alcohol (92–94% *w/w*) for 3 h under boiling conditions. Distilled water was added to the resulting soap solution, neutralized with an excess of 85% orthophosphoric acid, and left at room temperature for 15–20 h. After separation, the upper layer of fatty acids was washed with hot water 5–7 times and then dried with anhydrous sodium sulfate. The dried fatty acids were distilled under a vacuum.

Next, isobutyl esters of fatty acids were synthesized by esterification with isobutyl alcohol. The synthesis was performed by boiling the mixture with the collected reaction water in a Dean–Starke nozzle using p-toluenesulfonic acid as a catalyst. The synthesis conditions were as follows: a molar ratio of alcohol/fatty acids of 10:1, 1% of catalyst to fatty acids, and a reaction time of 10–15 h. The principal flowchart describing the synthesis of isobutyl esters is given in Figure 2.

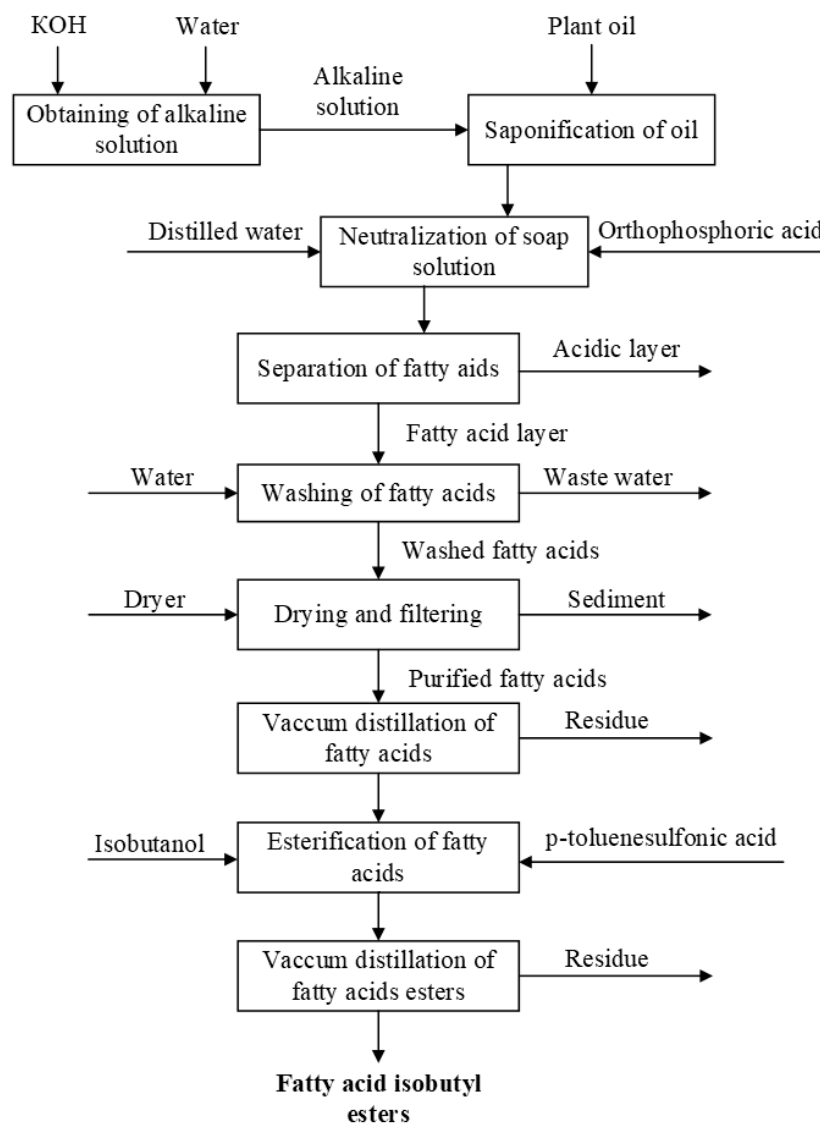


Figure 2. Flowchart of synthesis of isobutyl esters.

After synthesis, both ethyl esters and isobutyl esters were cleaned from alcohol and, after that, distilled under a vacuum (~0.1–0.3 kPa). An oil bath provided heating with a maximum operating temperature of up to 260 °C. Vacuum distillation is crucial in preparing bio-additives, setting them apart from other plant oil esters. This process removes unreacted substances and by-products formed during esterification and separates unwanted high-boiling components. As a result, it ensures higher purity, quality, and stability of the bio-additives [21]. The final products were stored in a vessel made of inert glass at room temperature without access to direct sunlight.

Within this study, the following fuel components were received by the methods described above: ethyl esters of coconut oil (CocOEE), isobutyl esters of coconut oil (CoIsoBE), ethyl esters of palm-kernel oil (PKOEE), and isobutyl esters of palm-kernel oil (PKIsoBE). The fatty acid composition of the esters was determined using an Agi-

lent 7890A gas chromatograph (Agilent Technologies, Inc., Santa Clara, California, U.S.) equipped with a splitting/no splitting gas flow injector, a flame ionization detector, and a J&W HP-5 capillary column. The capillary column characteristics were as follows: (5% phenyl)-methylsiloxane phase, length—30 m, inner diameter—0.32 mm, deposited phase thickness—0.25 μm . High-purity helium and hydrogen were used during the analysis. The authors' previous studies synthesized ethyl esters of rapeseed oil (ROEE) and ethyl esters of camelina oil (CamOEE) and used them in this work for comparison purposes. Their fatty acid composition was determined using the Agilent 7890A gas chromatograph equipped with a splitting/no splitting gas flow injector, a flame ionization detector, and an Agilent HP-88 capillary column. The capillary column characteristics were as follows: carrier—(88%—cyanopropyl) acrylic-polysiloxane, length—100 m, inner diameter—0.25 mm, deposited phase thickness—0.2 μm .

Selected physical–chemical properties of the renewable fuel components were studied by the following parameters: density at a temperature of 15 $^{\circ}\text{C}$, viscosity in a range of temperatures from minus 20 $^{\circ}\text{C}$ to 40 $^{\circ}\text{C}$, freezing point, and flash point. The properties of renewable fuel components were studied according to standard research methods [22–28]. The studies were performed at the Research Interactive Laboratory for Diagnostics of Operational Materials in Energy and Transport of Igor Sikorsky Kyiv Polytechnic Institute. To ensure the accuracy of the measurements and the results obtained, each parameter was measured three times for each sample, followed by a statistical error analysis (Appendix A).

3. Results

3.1. Analysis of the Chemical Composition of Renewable Fuel Components Based on Plant Oils

Figure 3 shows the fatty acid composition of esters based on coconut oil (CocO) and palm kernel oil (PKO) [19]. It is compared to the previously studied fuel components based on camelina oil (CamO) and rapeseed oil (RO) [19]. Both fuel components based on CocO and PKO are composed of fatty acids with shorter hydrocarbon chains than those based on CamO and RO. This difference is explained by the composition of the primary feedstock, i.e., oil. In the transesterification process, radicals of fatty acids, which are the main components of any oil, are transferred to esters without any changes. Accordingly, the fatty acid composition of the original oil determines the composition of the esters formed. By nature, CocO and PKO are fatty acids with relatively short hydrocarbon chains.

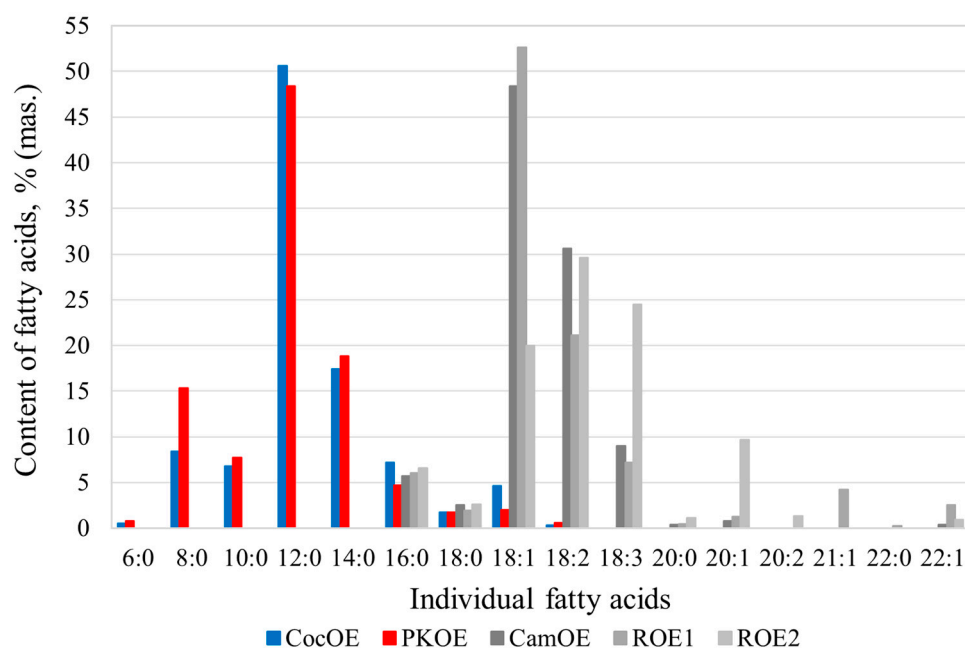


Figure 3. Fatty acid composition of plant oil esters, % (mas.).

The carbon number distribution of CocO and PKO esters is in the range of C₆–C₁₈. About 90% (mas.) of CocO esters and about 95% (mas.) of PKO esters are presented by saturated fatty acids C₈–C₁₆. Both components have a low content of unsaturated single- and double-bond C₁₈ fatty acids with only 5% and 2.6% (mas.), respectively.

However, the fatty acid composition of fuel components based on RO and CamO significantly differs from the ones mentioned above. The typical carbon number distribution is in the range C₁₆–C₂₂ with the most significant share of C₁₆–C₁₈ (up to 96% (mas.)) in CamO esters and C₁₆–C₂₀ (up to 94% (mas.)) in RO esters. Compared to CocO and PKO esters, these fuel components contain about 85–90% (mas.) of unsaturated fatty acids C₁₈–C₂₂ with one, two, and three double bonds. Such chemical composition and differences in the structure of ester molecules determine the properties of fuel components and their compatibility with conventional motor fuels.

3.2. Analysis of Basic Physical–Chemical Properties of Renewable Fuel Components Based on Plant Oils

Next, the properties of renewable fuel components based on plant oils were studied. The fatty acid composition causes the primary impact on their properties—the length of the hydrocarbon chain and the structure of individual molecules. Some effects are also caused by the molecular weight and structure of alcohols used during the esterification process.

It is seen from Figure 4 that the density of different plant oil esters varies in a range of 859–877 kg/m³. Typical ester molecules comprise two parts: hydrophobic radical of fatty acid and hydrophilic radical of alcohol. Such a composition determines the polarity of molecules and the ability to have intermolecular interactions. An in-depth explanation of the intermolecular phenomena found in oil esters is given in the previous study by the authors [19]. These intermolecular phenomena caused by the structure of molecules determine variations in the density values of different esters. As previously mentioned, CamOEE and ROEE are composed of molecules with higher carbon numbers, which results in stronger intermolecular interactions. Accompanied by higher molecular weight, CamOEE and ROEE possess higher density values than coconut oil and palm kernel oil esters.

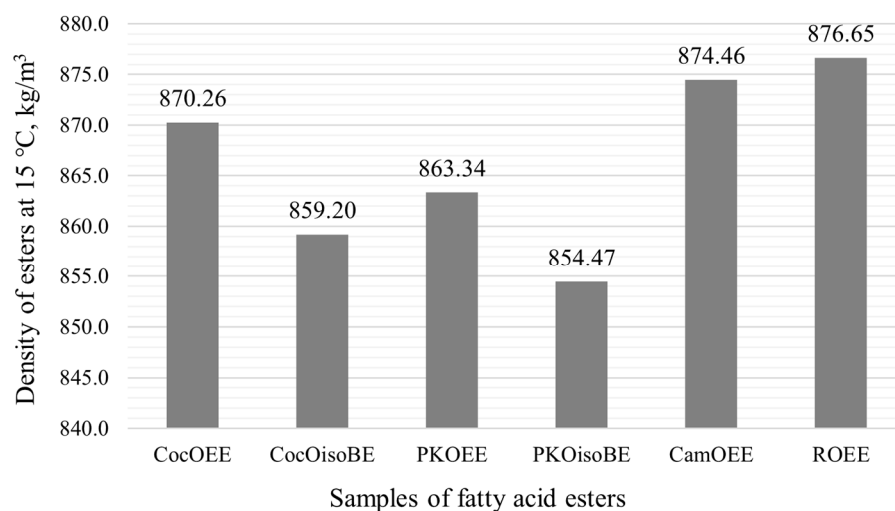


Figure 4. The density of plant oil esters at 15 °C, kg/m³.

The type of alcohol used for ester production also has a valuable effect on density. For both coconut oil esters and palm kernel oil esters, ethanol is replaced with isobutanol, which reduces density. This effect is explained by the isomerized structure of isobutanol, which determines the curvature of ester molecules and reduces their strength of intermolecular interaction forces. As a result, the density of CocOisoBE and PKOisoBE is diminished compared to corresponding ethyl esters.

The kinematic viscosity of renewable fuel components (Figure 5) significantly varies; its values range from 4.05–7.36 mm²/s at 20 °C. This variation is explained by the differences in the fatty acid composition of esters, mainly by the average molecular length and spatial orientation of molecules, and to some extent by the alcohol used for ester synthesis.

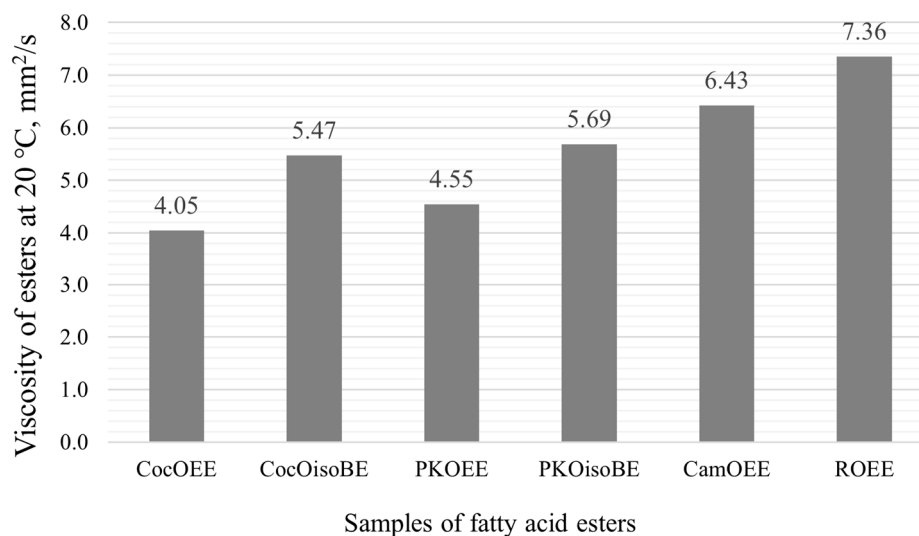


Figure 5. The viscosity of plant oil esters at 20 °C, mm²/s.

Like density, viscosity is a property that effectively characterizes the forces of intermolecular interactions in a liquid. Based on the abovementioned information, it can be deduced that the bigger the size of ester molecules, the greater the energy of interactions between them and, therefore, the higher their viscosity. This idea explains why CocOEE and PKOEE with carbon atom distributions of 8–16 have lower viscosity than RO and CamO esters with carbon atom distributions of 16–20. The rising viscosity values in a sequence of CocOEE–PKOEE–CamOEE–ROEE (Figure 5) correlate with the content and distribution of fatty acids in each studied ester (Figure 3).

A specific role that determines the fluidity of esters is the presence of unsaturated fatty acids with one and two double bonds. The double bond in the fatty acid structure forms a kink in a hydrocarbon chain, changing its spatial structure compared to that of analogous saturated fatty acid. This prevents the close packing of molecules and reduces intermolecular forces, lowering the viscosity.

Another effect on the viscosity of plant oil esters is caused by the type of alcohol used for their synthesis. Sequences of CocOEE–CocIsoBE and PKOEE–PKIsoBE (Figure 5) show a corresponding rise in viscosity values. The reason for this effect is the length of the alcohol radical. A longer radical of isobutyl alcohol results in stronger intermolecular forces and, consequently, higher viscosity. Moreover, the branched structure of isobutyl alcohol introduces steric hindrance, affecting the esters' fluidity [22].

To study and understand the fluidity of the renewable fuel components based on plant oils in more detail, the viscosity–temperature characteristics of fatty acid esters were further investigated. Figure 6 shows that all samples of plant oil esters show a common tendency to increase viscosity with decreasing temperature. This is typical for fuels, as a decreasing temperature reduces the thermal energy of motion and the mobility of molecules. A decrease in temperature leads to an increase in association and a rise in the esters' viscosity.

As the temperature decreases to below 10 °C and lower, the difference between the viscosity values of plant oil esters becomes more pronounced. CocOEE and PKOEE reveal a relatively smooth dependence of viscosity on temperature, having significantly lower values at the same temperatures as other oil esters.

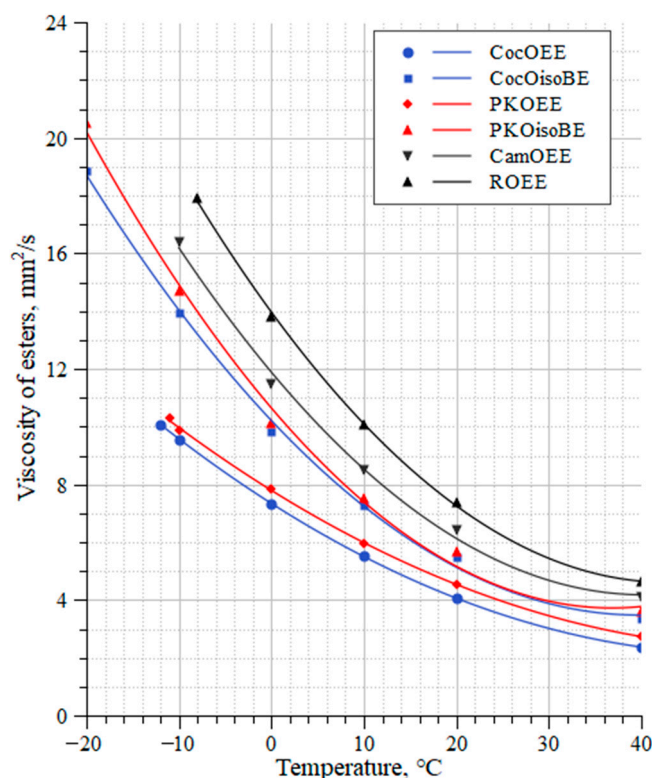


Figure 6. The viscosity of plant oil esters as a function of temperature.

It should be noted that CocOEE and PKOEE lose their fluidity at minus 12 °C with a viscosity value of 12.2 mm²/s and minus 11 °C with 10.3 mm²/s. A different effect is observed for ROEE and CamOEE, which retain their fluidity at much higher viscosity values. Maintaining the fluidity of ROEE and CamOEE even at high viscosity values may be explained by the effect of the spatial structure of unsaturated fatty acids, which was described earlier. Conversely, the prevailing share of long-chain ester molecules results in early solidification (at minus 10 °C reaching 16.4 mm²/s and at minus 8 °C reaching 17.9 mm²/s). In contrast, short-chain saturated molecules of CocOEE and PKOEE, which can be packed easily, maintain low viscosity values with comparatively early loss of fluidity.

Different results are observed for the viscosity–temperature dependence of CocOisoBE and PKOisoBE. As Figure 6 shows, they are characterized by higher viscosity values than analogous esters derived using ethanol for the above reasons. However, the effect of steric hindrances due to the branched structure of isobutyl alcohol is quite visible. It contributes to maintaining the fluidity of esters at comparatively low temperatures (below minus 20 °C).

Low-temperature properties characterized by the freezing point of renewable fuel components were studied next. Values of the freezing point, describing the temperatures at which liquid transforms into a solid substance, are shown in Figure 7. The overall tendency of the studied plant oil esters to freeze at low temperatures is generally similar. It continues the pattern of change in viscosity characteristics with decreasing temperature, which was described above.

As mentioned above, intermolecular forces, which exist between molecules of esters, cause their slight chaotic movement. As the temperature drops, the association of molecules intensifies quickly. This happens partly because the thermal motion of the molecules decreases, strengthening the bonds between them, and partly because the mobility of the ester molecules, which interconnect with each other, also decreases.

Comparatively high values of the freezing point of CocOEE and PKOEE are explained by the predominant content of saturated fatty acid radicals in the composition of esters. The reason for the high freezing point of ROEE and CamOEE is the high content of long-chain

fatty acid radicals. At the same time, it is noted that ROEE reaches its freezing point at a lower temperature.

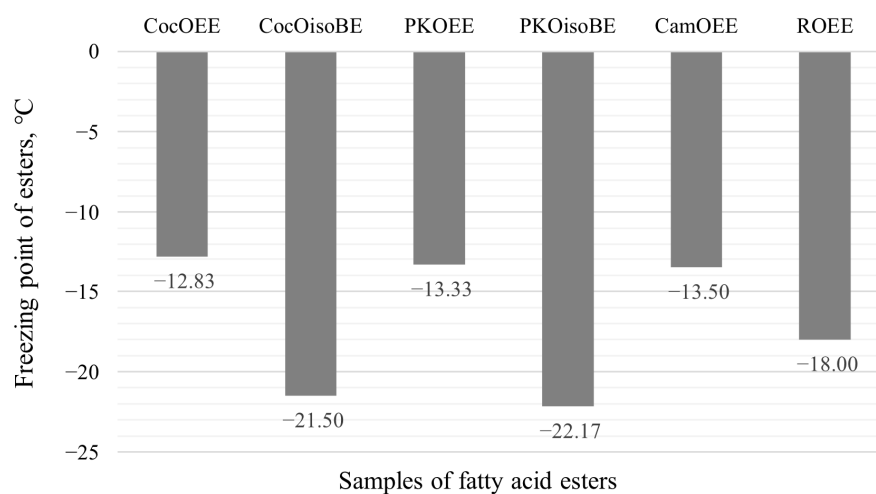


Figure 7. The freezing point of plant oil esters, °C.

CocIsoBE and PKOisoBE have the lowest freezing points (minus 21.5 °C and 22.2 °C) among the studied samples. This result is reached due to the steric structure of isobutyl alcohol, which prevents the interconnection of molecules and, therefore, the early solidification of esters.

4. Discussion

The above results give grounds for assessing the compatibility of studied renewable fuel components with conventional motor fuels and the possibility of their full or partial replacement.

As mentioned earlier, biofuels produced from plant oil are considered an alternative to conventional diesel fuel or kerosene. Table 1 provides comparative characteristics of the studied renewable fuel components and standard requirements of commercially available fuels: kerosene [29,30], mineral diesel fuel [31], and biodiesel fuels based on methyl and ethyl esters [32,33]. Analyzing the given data shows that most properties are comparable to standard requirements. CocIsoBE, PKOisoBE, CamOEE, and ROEE may be used to entirely replace mineral diesel fuel or produce high-level biodiesel blends according to the standard EN12214. All of the studied renewable fuel components may be used for 5% or 7% blending with mineral diesel fuel to meet the EN 590 standard, which determines the requirements for conventional diesel fuel with low concentrations of esters. Using esters synthesized with isobutyl esters may be beneficial from the point of view of providing good low-temperature properties, as well as improved chemical stability and prolonged storage periods without the deterioration of its properties. Using the studied renewable fuel components in aviation fuels (biokerosene) may only be considered for partial replacement. This is because of the insufficient fluidity and low-temperature properties of plant oil ester. At the same time, it may be expected that CocOEE, CocIsoBE, PKOEE, and PKOisoBE could provide a higher-concentration blend than CamOEE and ROEE, providing better chemical stability.

Table 1. Comparative characteristics of renewable fuel components and standard requirements for commercial fuels.

Fuel Property	Unit of Measurement	ASTM D7566 [30]	EN 590 [31]	EN14214 [32]	CocOEE	CocOisoBE	PKOEE	PKOisoBE	CamOEE	ROEE
Density at temperature 15 °C	kg/m ³	775–840	820–845	860–900	870.35	859.21	863.34	854.54	874.5	876.59
Viscosity at temperature: minus 20 °C, max 40 °C	mm ² /s	8 -	- 2.0–4.5	- 3.5–5.0	n/a* 2.37	18.83 3.36	n/a 2.73	20.52 3.57	n/a 4.09	n/a 4.62
Freezing point, max	°C	minus 47	-	Location & season dependent	minus 12.83	minus 21.5	minus 13.33	minus 22.17	minus 13.5	minus 18.0
Cold filter plugging point, max	°C	-	5–minus 20		n/a	n/a	n/a	n/a	minus 8	minus 14
Flash point, min	°C	38	55	101	112.08	115.77	110.42	113.00	167.2	170.25
Copper strip test	Class	1	1	1	1a	1a	1a	1a	1b	1b

* data are not available.

The results allow us to understand the impact of renewable fuel components' chemical and fatty acid compositions on their basic physical–chemical properties. The selection of different types of feedstock, i.e., plant oils and alcohols, for the synthesis of esters within this study allowed us to determine the main factors that influence its properties. Among them are the carbon number distribution of fatty acid radicals and unsaturated fatty acid radicals with one, two, or more double bonds. According to the general trend, increasing the carbon chain length increases the density and viscosity and worsens low-temperature properties. Along with this, the rising content of unsaturated fatty acids contributes to improving fluidity and low-temperature properties. These dependencies allow the proper feedstock selection to receive renewable fuel components with desired properties. The carbon chain length and spatial structure (degree of isomerization) of alcohol radicals are other factors influencing the properties of esters. The rising carbon number in alcohol radicals leads to an increase in viscosity and density. An important parameter is the isomerization of alcohol radicals; this results in a significant improvement in the esters' fluidity and low-temperature characteristics, as well as a reduction in density. Such a characteristic of impact allows for modifying the properties of renewable fuel components during the production process, especially in conditions of limited feedstock availability.

Apart from the effects studied and discussed, the composition and structure of plant oil esters have visible effects on other physical–chemical, operational, and environmental properties. Mostly, these effects are controversial. Plant oils with a high molecular composition will possess a heavier fractional composition, which is usually undesired. While unsaturated fatty acids positively affect fluidity, they have significantly lower chemical and oxidation stability due to double bonds. The feedstock selection with short-chain fatty acid composition will reduce fuel components' energy content because of the increasing ratio of oxygen atoms per molecule. The specific feature of all renewable fuel components is the comparatively high flash point, which improves fuel fire safety.

The overall benefit of renewable fuel components based on plant oils is their environmental safety (higher biodegradability, lower toxicity, and natural origin) and reduced greenhouse gas emissions.

Despite the promising results, several challenges remain in substituting conventional fuels with renewable alternatives. Among the technical difficulties is the compatibility of biofuels with existing engines and fuel systems. While the studied renewable fuel components are compatible with conventional fuels, issues may still be related to material compatibility, engine performance, and emissions.

The economic challenges may be related to difficulties in scaling production. Scaling up to meet fuel demands even at the regional level will require significant investment in infrastructure and technology. Additionally, the availability and cost of feedstock production and supply can vary widely.

Furthermore, regulatory challenges may arise at the stage of new biofuels' approval for use. This process may require developing new normative documents or implementing changes to existing ones to ensure that biofuels meet stringent environmental and performance standards.

The results of this study provide a wider range of topics for future research. In particular, further research should aim at studying other properties of renewable fuel components, like energy properties, chemical and oxidation stability, compatibility with operation materials, the development and study of optimal blends with conventional fuels, and the selection of new types of oils based on the discovered dependencies of properties of feedstock and final products.

5. Conclusions

This work presents the results of the study of basic physical–chemical properties of renewable fuel components based on rapeseed, camelina, coconut, and palm kernel oils. Based on experimental results, the dependences of properties on the composition of plant oils and alcohol used for synthesis were found and substantiated.

The influence of plant oil composition is revealed due to the length of the carbon chain of the fatty acid radicals and the degree of their saturation. Increasing the length of fatty acid radicals results in the strengthening of forces of intermolecular interaction that consequently increase the density, viscosity, and low-temperature properties of esters. The presence of unsaturated fatty acid radicals results in changes in the spatial structure of molecules with the consequent weakening of forces of intermolecular interaction. This is revealed by reducing the viscosity and freezing point of renewable fuel components. The presence of two or more double bonds in fatty acid radicals further intensifies the described effect.

The influence of alcohol on the properties of esters is revealed due to the length of the carbon chain of an alcohol radical and its isomerization. Increasing the carbon chain length has an effect similar to those described for fatty acid radicals. The isomerization of alcohol weakens the intermolecular interaction forces, consequently reducing the density and freezing point of renewable fuel components.

Our assessment of the compatibility of renewable fuel components with conventional motor fuels allowed us to draw the conclusion that they may be used for partial and complete replacement of mineral diesel fuels and partial replacement in low concentrations of conventional aviation fuel. The developed dependencies of feedstock properties provide fundamentals for the optimal selection of plant oil for biofuel production and the modification of its properties via the selection of the type of alcohol. This study's findings will benefit the biofuel industry's development, particularly in Ukraine, and the deployment of renewable energy sources.

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Appendix A

The accuracy of the experimental measurements and results was estimated by performing a statistical error analysis of the data.

The arithmetic mean values \bar{x} of the data were calculated as:

$$\bar{x} = \frac{1}{N} \sum x_i, \quad (\text{A1})$$

where N —number of measurements

x_i —measured value.

Standard deviation S was calculated as the square root of the variance:

$$S = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N - 1}}. \quad (\text{A2})$$

Standard error $S_{\bar{x}}$ was calculated as:

$$S_{\bar{x}} = \frac{S}{\sqrt{N}}. \quad (A3)$$

Variance Var_x was calculated as:

$$Var_x = \frac{1}{1-N} \sum (x_i - \bar{x})^2. \quad (A4)$$

Table A1 analyzes the statistical errors in experimental studies on the density of renewable fuel components. It shows that the maximum values of standard deviations and standard errors do not exceed the units of measurement in the range of the studied parameters. The standard deviation of density measurement is 0.20–0.38 for the studied plant oil esters.

Table A1. Statistical error analysis of density measurements.

Sample	N	\bar{x}	S	$S_{\bar{x}}$	Var_x
CocOEE	3	870.26	0.6496922348312	0.3750999866702	0.4221
CocIsoBE	3	859.2033333333	0.3400490160746	0.1963273909683	0.115633
PKOEE	3	863.3366666667	0.5050082507577	0.2915666495179	0.255033
PKIsoBE	3	854.47	0.4194043395102	0.2421432083155	0.1759
CamOEE	3	874.4633333333	0.4162130864513	0.2403007375029	0.173233
ROEE	3	876.6466666667	0.4476978147516	0.2584784538624	0.200433

An analysis of the statistical errors of experimental studies on the kinematic viscosity of renewable fuel components in a selected temperature range is presented in Table A2. It is seen that the maximum values of standard deviations and standard errors do not exceed the units of measurement in the range of studied parameters. The standard deviation of kinematic viscosity measurement is in the range of 0.006–0.055 for the studied plant oil esters.

Table A2. Statistical error analysis of viscosity measurements.

Sample	N	\bar{x}	S	$S_{\bar{x}}$	Var_x
at 40 °C					
CocOEE	3	2.372	0.02107130750571	0.0121655250606	0.000444
CocIsoBE	3	3.3623333333333	0.02159475244899	0.01246773613951	0.000466
PKOEE	3	2.7326666666667	0.02212088003072	0.01277149604045	0.000489
PKIsoBE	3	3.5763333333333	0.03098924544634	0.01789164920043	0.00096
CamOEE	3	4.0973333333333	0.02968725877095	0.01713994684291	0.000881
ROEE	3	4.6476666666667	0.03027099822162	0.01747696897189	0.000916
at 20 °C					
CocOEE	3	4.046	0.01705872210923	0.009848857801796	0.000291
CocIsoBE	3	5.4746666666667	0.01582192571507	0.009134793070696	0.00025
PKOEE	3	4.5486666666667	0.01320353488023	0.007623064417353	0.000174
PKIsoBE	3	5.6906666666667	0.02200757445366	0.01270607903503	0.000484
CamOEE	3	6.4256666666667	0.01975685535032	0.01140662575485	0.00039
ROEE	3	7.3576666666667	0.0141891977692	0.00819213715163	0.000201

Table A2. Cont.

Sample	N	\bar{x}	S	S_x	Var_x
at 0 °C					
CocOEE	3	7.543666666667	0.02272296928954	0.0131191124361	0.000516
CocOisoBE	3	9.842	0.02206807649071	0.01274100990241	0.000487
PKOEE	3	7.832	0.02107130750571	0.0121655250606	0.000444
PKOisoBE	3	10.133333333333	0.01921804707387	0.0110955446514	0.000369
CamOEE	3	11.484333333333	0.02379775899814	0.01373964256368	0.000566
ROEE	3	13.810333333333	0.02350177298276	0.01356875495803	0.000552
at minus 8 °C					
ROEE	3	17.891333333333	0.02003330560176	0.01156623438193	0.000401
at minus 10 °C					
CocOEE	3	9.523333333333	0.02218858565419	0.01281058590038	0.000492
CocOisoBE	3	13.966666666667	0.01422439219557	0.00821245666317	0.000202
PKOEE	3	9.864666666667	0.01193035344545	0.006887992773257	0.000142
PKOisoBE	3	14.670333333333	0.02250185177565	0.01299145017994	0.000506
CamOEE	3	16.411333333333	0.02003330560176	0.01156623438193	0.000401
at minus 11 °C					
PKOEE	3	10.283333333333	0.02715388247256	0.01567730135507	0.000737
at minus 12 °C					
CocOEE	3	12.233333333333	0.02218858565419	0.01281058590038	0.000492
at minus 20 °C					
CocOisoBE	3	18.876	0.09568698971125	0.05524490926773	0.009156
PKOisoBE	3	20.519666666667	0.0265015722804	0.01530068989004	0.000702

Table A3 presents an analysis of the statistical errors in the experimental studies on the freezing point of renewable fuel components. The maximum values of standard deviations and standard errors do not exceed the units of measurement in the range of the studied parameters. The standard deviation of the freezing point measurement is in the range of 0.17–0.29 for the studied plant oil esters.

Table A3. Statistical error analysis of freezing point measurements.

Sample	N	\bar{x}	S	S_x	Var_x
CocOEE	3	−12.833333333333	0.2886751345948	0.1666666666667	0.083333
CocOisoBE	3	−21.5	0.5	0.2886751345948	0.25
PKOEE	3	−13.333333333333	0.2886751345948	0.1666666666667	0.083333
PKOisoBE	3	−22.166666666667	0.2886751345948	0.1666666666667	0.083333
CamOEE	3	−13.5	0.5	0.2886751345948	0.25
ROEE	3	−18	0.5	0.2886751345948	0.25

In summary, mathematical data processing and statistical error analysis allowed us to draw conclusions about the sufficient accuracy of measurements and sufficient reliability, indicating precise and consistent results.

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