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ORIGINAL PAPER

Current Challenge and Innovative Progress for Producing HVO and FAME Biodiesel Fuels and Their Applications

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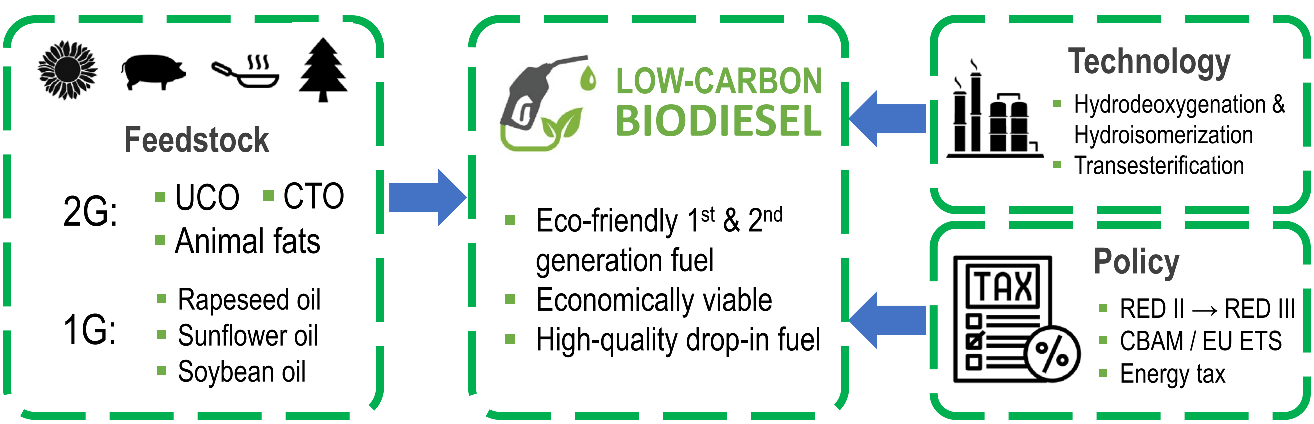
Abstract

Current petroleum issues, quickly raising its costs and uncertainties regarding petroleum fuels availability endanger the renewable and sustainable challenge of the worldwide economy. Both the ecological consideration and availableness of fuels highly impact fuel directions for transport vehicles. The current paper introduces the Prospects for producing hydrotreated vegetable oil (HVO) and fatty acid methyl esters (FAME) biodiesel fuels and their applications. The potential of raw material supply for the production biodiesel in Russia was examined, including sunflower oil, soybean oil, rapeseed oil, tall oil, and used cooking oil. Additionally, an economic evaluation of biodiesel production in Russia was performed. Likewise, Russia has launched the process of developing low-carbon strategies for the energy transition, but the country is placing more emphasis on the electrification and gasification of transport. The results reported that HVO is a promising low-carbon component of biological nature than FAME, according to it has a high calorific value, and great chemical stability. Furthermore, the results indicated that the most promising feedstock for biodiesel production in Russia is rapeseed oil, as rapeseed retains a higher yield growth potential. Finally, the most preferable option is the hydroprocessing of oils in a separate unit with a capacity of 500,000 tons/year for oil. Large capacity is probably redundant given the limited resources of advanced raw materials up to 100–150,000 tons of waste oils and up to 150–200,000 tons of tall oils.

Graphical abstract



Keywords Biodiesel · Hydrotreated vegetable oil (HVO) · Fatty acid methyl esters (FAME) · Biofuel · Alternative fuels · Low carbon-diesel fuels

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Abbreviations

HVO	Hydrotreated Vegetable Oil
FAME	Fatty Acid Methyl Esters

EU	European Union
HEFA	Hydroprocessed Esters and Fatty Acids
SAF	Sustainable Aviation Fuel
RED	Renewable Energy Directive
ILUC	Indirect Land Use Change
CBAM	Carbon Border Adjustment Mechanism
ETS	Emission Trading System
UCO	Used Cooking Oil
HOLL	High Oleic Low Linolenic
CTO	Crude Tall Oil
$/t	Dollar per tones
ASTM	American Standards for Testing and Materials

Statement of Novelty

The current study investigated prospects for the supply of renewable diesel fuel from Russia to European Union. Furthermore, the potential of raw material supply to produce biodiesel in Russia was also demonstrated. The potential was involved sunflower oil, soybean oil, rapeseed oil, tall oil, as well as used cooking oil. Additionally, the key task is to ensure the competitiveness and sustainable economic growth of Russia in the context of the global energy transition. Finally, an economic evaluation of biodiesel production in Russia was also shown in the article.

Introduction

Petroleum fuels are not a form of renewable and sustainable energy, their supplies are restricted, and their manufacturing requires thousands of years [1–5]. The comprehensive utilization of oil derivatives in current years has led in the energy issue, ecological pollution, and numerous issues for health of humans [6–11]. More than 80% of the energy in the worldwide reaches from petroleum fuels like burning conventional fuel, gasoline, and diesel [12–15]. Petroleum fossil fuels are the major source of energy generation in the last decades [16–20]. It is necessary to produce new biofuels with properties comparable to petroleum fuels [21–24]. One of the most decisive fuels for substituting petroleum fuels is biodiesel [25, 26]. It is a clean and renewable and sustainable energy that can affect positively the atmosphere [27, 28]. Recently, the global market for low-carbon diesel fuels is represented by two products, including fatty acid methyl esters (FAME) and hydrotreated vegetable oils (HVO) [29]. The production of these components is based on the same raw materials, involving vegetable oils for food and non-food purposes, animal fats, waste oils. Nevertheless, fundamentally various ways of chemical transformation of the original molecules of triglycerides and fatty acids are utilized. The choice of the way of vegetable raw materials conversion has a decisive impact on the composition and properties of the resulting fuels. Table 1 shows the physicochemical and performance characteristics of FAME and HVO.

During the production of FAME, triglycerides undergo transesterification with methanol, while retaining a high oxygen content, as well as double bonds of the original fatty acids [33]. At the same time, in the production of HVO, complete hydrogenation of fatty acids takes place with the removal of heteroatoms and the saturation of double bonds. This leads to a significantly higher calorific value of HVO, as well as greater chemical stability [34]. Hydroisomerization of normal paraffins is also executed to maximize the low temperature properties of hydrotreated vegetable oils. Consequently, the low temperature properties of HVO are significantly superior to FAME. Most of the structure of the original fatty acids is retained in the final product in the production of FAME [35]. Thus, the characteristics of the feedstock oil have a decisive influence on the performance of the renewable fuel component. The structure and composition of the oil is less important for HVO. Since regardless of the ratio of saturated and unsaturated fatty acids after hydrogenation, the target product will contain only C_{16}–C_{20} normal paraffins. This will then be subjected to hydroisomerization. Figure 1 summarizes the Pathway of biodiesel production and its properties.

The largest producer and consumer of biodiesel in the world is European Union (EU). The production capacity of FAME in EU is excessive, and the growth potential of its production is limited by the ultimate share of its involvement in diesel fuel [39]. This share appreciated by 7% and has already been achieved in most European countries. Figure 2 displays the average share of biodiesel components in EU countries. HVO is more promising product, due to the

Table 1 Physicochemical and performance properties of FAME and HVO [30–32]

Parameter	FAME	HVO
Density at 15 °C, kg/m^3	873–885	770–780
Kinematic viscosity, mm^2/s	4.5–5.1	2.8–3.0
Cetane number	49–55	75–90
Net calorific value, MJ/kg	39.8–40.4	43.8–44.1
Mass fraction of oxygen, wt.%	10.7–11.1	0
Oxidative stability, h	3–8	> 24
Cloud point, °C	−5 ± 15	Lower than −20.0
Maximum filterability temperature, °C	−7 ± 13	Lower than −20.0
Fractional composition:		
Distilled volume at 250 °C, vol.%	0–5	15–30
Distilled volume at 350 °C, vol.%	90–100	100
The maximum allowable content in diesel fuel according to EN 590, vol.%	7	Not limited

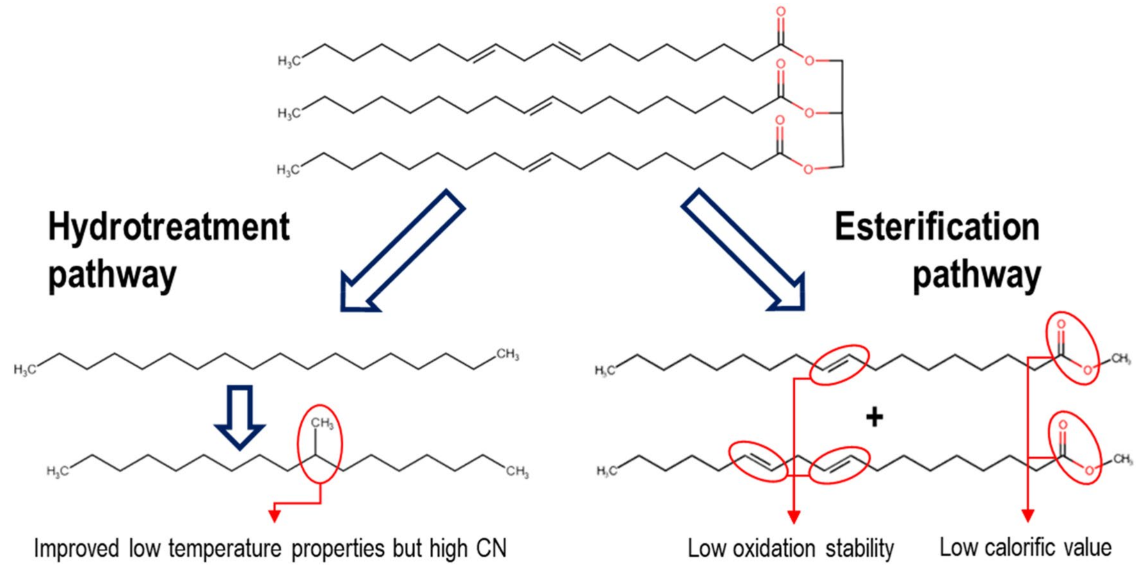


Fig. 1 Pathway of biodiesel production and its properties [36–38]

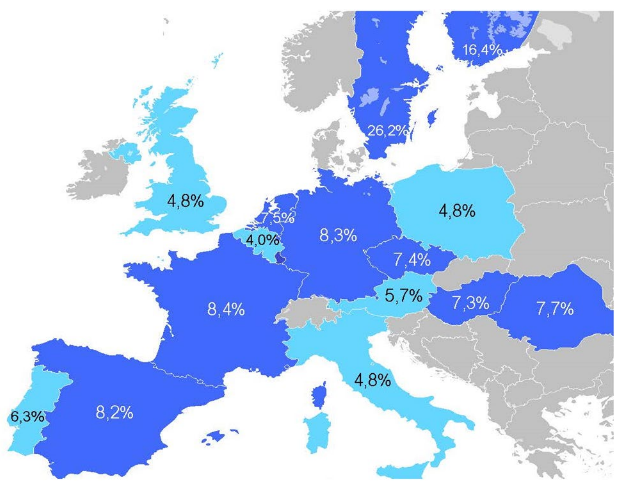


Fig. 2 Average share of biodiesel components in EU countries [42]

absence of a limit on the maximum concentration of input into diesel fuel and higher performance. The production of HVO also allows further production of hydroprocessed esters and fatty acids (HEFA). This is a sustainable component of jet fuels. Given EU policy towards regulating the content of sustainable aviation fuel (SAF) from 2025 and this fact has a great importance.

Support Measurements for Renewable Diesel in EU and Russia

Promotion of the production of renewable fuels, involving biodiesel, in the countries of European Union is executed through a set of directives [40]. None of the directives sets requirements for the production and consumption of biodiesel specifically. The purpose of the directives is to set the bar for decarbonization accessible to all countries of European Union, involving in the transport sector. Each of EU members is free to independently choose the direction of energy development according to its capabilities and resources to achieve aa a given goal [41].

From July 1, 2021, a new version of one of the most important directives, containing the directive on Renewable Energy Directive (RED II) will be introduced into the legislative field to replace the 2009 version (RED I) [43]. The use of biofuels by 2030, according to the directive, should reach at least 14% and the target was 10% by 2020 as the efforts done be [43–45]. It is important to observe that the consumption of renewable energy in the transport sector is being explained. Each EU country is obliged to establish such requirements for suppliers in order to eventually fulfill the minimum requirement. The contribution of advanced biofuels and biogas to final energy consumption in the transport sector should be at least 0.2% in 2022, at least 1% in 2025, as well as at least 3.5% in 2030. Advanced fuels according to RED II directive are fuels produced from the raw materials specified in Table 2. Likewise, most of them are waste from various agricultural, cellulose industries, algae, etc.

As part of the fight against climate change in the form of a goal to achieve zero emissions in 2050, a package of

Table 2 List of raw materials, during the processing of which advanced biodiesel is obtained according to RED II [46]

Raw material	Reduction of greenhouse gas emissions according to emission estimates for EU, %	Reduction of greenhouse gas emissions estimated, %	Content limit, %
Waste from palm oil production	–	–	Not less than 3.5 (including multiplier 2)
Seaweed	–	–	
Mixed municipal waste	–	–	
biological waste	43–86	20–80	
Straw	80–88	76–85	
Bagassa	87–93	85–91	
Ears without corn grains	82	82	
Forest industry waste	–	–	
Other non-edible cellulosic materials	–	–	
Used cooking oil	88	84	No more than 1.7
Animal fats	84	78	

legislative acts called "Fit for 55" was released in July 2021. The package proposes to make a number of changes related to the achievement of the goal of reducing emissions by 55% by 2030 in a variety of directives, involving RED II directive [46]. The new concept of the directive proposes to decrease emissions by 2030 by at least 55% compared to 1990 in order to guarantee carbon neutrality by 2050. To stimulate the production of synthetic fuels, an ambitious goal for non-biological fuels of 2.6% is introduced. These include e-fuels, green hydrogen for transport and in oil refining. The goal for advanced fuels is reduced to 2.2%, but the multiplier "2", which actually means an even more ambitious goal than it was before 3.5% under RED II directive due to the multiplier [46]. For biofuels from food and feed crops, the goal remains the same—no more than 7%, and an increase of no more than 1% compared to the value for 2019 [47–49]. The new concept replaces 14% of target for renewable energy in transport. This is with a target of 13% reduction in greenhouse gas intensity in transport by 2030 compared to a baseline of intensity with conventional fuels. This means that cleaner fuels will contribute more to the goal. The threshold for fuel use is proposed to be a reduction in emission intensity by 65%. At the same time, 13% reduction in emission intensity would require more biofuels than under RED II directive [46]. The comparison of RED I, RED II, and RED III Directives targets is illustrated in Fig. 3.

As part of the Fit for 55 packages, the existing energy taxation system is also being revised and a differentiated scale is being introduced from 2023, implying various rates for fossil fuels and biofuels [51]. This is with considering their origin, including the risk of indirect land use change, such as Indirect Land Use Change (ILUC), as well as the possibility of using raw crops as food and referring to advanced fuels. For sustainable biofuels, the difference in taxation compared to petroleum diesel will reach 5.37 EUR/GJ, and for advanced biofuels will be 10.60 EUR/GJ. Table 3 presents the tax rates for certain fuels.

The stimulating policy of the European Union crosses the "border" from 2023 cross-border carbon tax, such as Carbon Border Adjustment Mechanism (CBAM) is introduced on imported products, depending on their carbon intensity. Despite the fact that the oil industry has not yet entered the industries regulated by the mechanism, there is no doubt that oil products will be taxed. The reason for their absence in

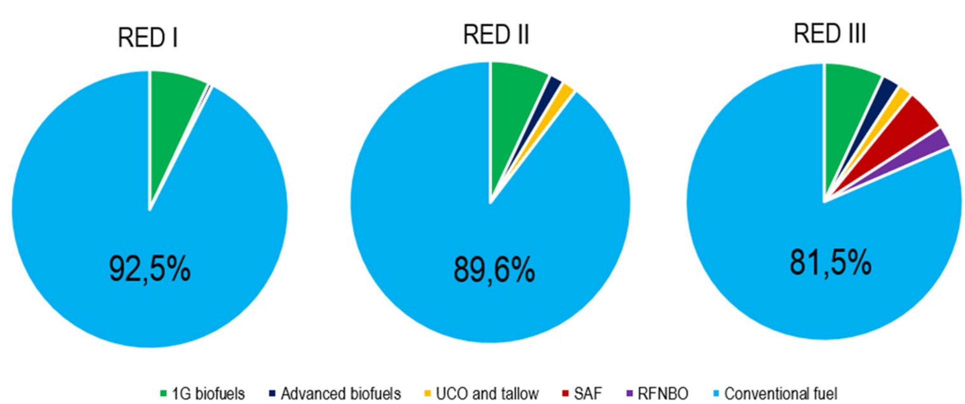


Fig. 3 Comparison of EU Renewable Directives targets [46, 50, 51]

Table 3 Tax rates for certain fuels [46]

Type of fuel	Tax rate at the beginning of the transition period (01/01/2023), EUR/GJ	Tax rate at the end of the transition period (01/01/2033), EUR/GJ
Petroleum diesel fuel	10.75	10.75
Unsustainable biofuels and biofuels with high ILUC risk	10.75	10.75
Sustainable biofuels from food or feed raw materials	5.38	10.75
Renewable non-biological fuels (hydrogen/e-fuels produced with renewable electricity)	0.15	0.15
Advanced biofuels under RED II Annex IX	0.15	0.15

the current document is related to the technical difficulties of preparing a standard calculation of life cycle emissions, and not the doubts of the European Commission regarding their inclusion. Russia, as a supplier of products with a high carbon footprint, may further suffer from the introduction of CBAM, involving due to the supply of diesel fuel. Importing countries can avoid paying CBAM if the country is included in the Emission Trading System (ETS) of EU, or if they develop their own exhaust emissions trading system. In Russia, there are no analogues of the main tools for the development of the industry utilized in EU, as well as the mechanisms for subsidizing agriculture have no relationship with the production of transport biofuels. Carbon regulation in general is just beginning to emerge.

The first step towards the implementation of our own carbon regulation system was the adoption in July 2021 of the federal law, involving On Limiting Greenhouse Gas Emissions. The law obliges all organizations with greenhouse gas emissions of more than 150,000 tons/year to report on emissions. The adopted law does not provide for the use of active instruments of climate regulation, including the introduction of a carbon tax or emission quotas at the federal level. At the same time, participation in climate projects, the creation and state support of which is provided for by the document, may be attractive for companies. At the same time, participants in such projects have the right to transfer carbon units to other legal entities, which lays the foundation for trading carbon units in the future. The implementation of climate projects is designed to reduce the “carbon footprint” of Russian products. So that the mechanism for the production and transfer of carbon units is attractive to Russian exporters in the light of the prospects for the introduction of a border carbon levy by EU [52].

The experiment on special regulation of emissions and absorption of greenhouse gases in the Sakhalin Region is enshrined in the draft federal law and the road map. The experiment runs from January 1, 2022 to December 31, 2026. For enterprises whose activities are accompanied by more than 50,000 tCO_2-eq till 2024 and 20,000 tCO_2-eq from 2024. Emission quotas will be fixed, if exceeded, fines of 150 Rubbles ($1.96) per ton of CO_2-eq will be imposed.

In November 2021, the government approved the Strategy for the Social and Economic Development of Russia with Low Greenhouse Gas Emissions till 2050. The strategy includes two scenarios, involving inertial and target (intensive) [52]. The target scenario is taken as a basis. The scenarios differ in the set of measures to decarbonize the Russian economy. In the target scenario, the main task is to ensure the competitiveness and sustainable economic growth of Russia in the context of the global energy transition. However, to decrease greenhouse gas emissions, the strategy provides for the widespread gasification and electromobilization of transport without affecting the requirement for biofuel production.

Prospects for the Supply of Renewable Diesel Fuel from Russia to European Union

Commissioning of biodiesel production capacities in Russian Federation in the context of the current policy in the field of renewable energy is possible only if the project is fully focused on imports to EU [53]. Consequently, it is important to assess the value of promising monetary incentives aimed at equalizing the cost of oil and renewable fuels and affecting the functioning of suppliers external to EU. From the analysis executed in the previous section, it can be seen that the only real monetary incentives are the energy content tax and the prospective introduction of CBAM. For these two mechanisms, real unit payments were calculated for the horizon up to 2035 in the context of three types of fuel, including petroleum diesel fuel, used cooking oil (UCO) and fats, pure HVO from first generation feedstock, as well as pure HVO from second generation feedstock [54]. The calculation is based on the existing prerequisites for the growth in the cost of carbon dioxide, as well as the mechanism for introducing CBAM, by analogy with the metallurgical sector. The calculation results are illustrated in Fig. 4. What’s more, this shows that the studied types of diesel fuels, which will have a significantly different tax burden. Likewise, the value of which will be sufficient to compensate for the difference in the cost of raw materials in the case

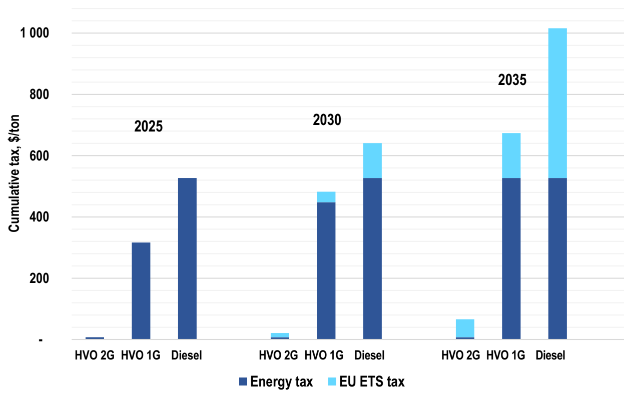


Fig. 4 Fuel tax rates up to 2035s [53, 56]

of first-generation raw materials, as well as UCO and fats. Nevertheless, these support measures may not be enough to develop the production of advanced fuels.

In the case of biofuels from first generation feedstocks, UCO and fats, in addition to the economic efficiency parameter, the size of the potential biodiesel market in EU is also important in the context of the current policy to limit the consumption of certain types of biofuels [53]. The forecast of potential volume, in turn, largely depends on the consumption of biodiesel in EU, which varies greatly from the expected energy consumption in the transport sector. Taking into account various programs aimed at maximizing the design of engines in order to reduce fuel consumption. Moreover, this aimed to general trends towards a decrease in the use of personal vehicles and the general population of Europe by 2030 a decline in energy consumption in transport of up to 20% is predicted [55].

For a broader scenario assessment of the potential for increasing biodiesel consumption, three scenarios will be considered, including with a low (-10%), medium (-15%), as well as high (-20%) [57]. The decrease in energy consumption relative to the value in 2019 is 289 million tons of oil. The target values may also be affected by the rejection or adoption of the Fit for 55 legislative packages. Its adoption will not change the restrictions on the consumption of first-generation fuels from UCO and animal fats [58]. Additionally, the market capacity limits for these fuels are of the greatest importance, since advanced fuels are not limited by the upper limit [59]. The target structure for the consumption of various types of biofuels and scenarios for reducing energy consumption in the transport sector in the context of diesel fuels are taken in the considerations [60]. Therefore, it is possible to predict the potential for raising the consumption of different biodiesel fuels by type of raw material utilized for their production [61]. Table 4 presents the assessment of the potential for increasing the consumption of biodiesel components in accordance with the target structure.

The results reported that the real potential for increasing consumption for first-generation biofuels ranges from 0 to 0.9 million tons. This is associated with fairly strict restrictions on their share in total energy consumption, which is no more than 1% higher compared to 2019. Nevertheless, this value will be not higher than 7% in the total share, as well as with the possibility of increasing to 2% with zero or near zero consumption in 2019 [60]. This makes practically it possible to increase the share from 3.5% at the moment to about 4.5% in 2030. This will be with an assumption no growth in consumption of other first-generation biofuels, such as bioethanol. The increment is fully offset in the ultimate decline scenario. For fuels based on UCO and animal fats, the situation is similar, but the possibility of growth is even lower from the current 1.5% to 1.7% in 2030 in accordance with the restrictions in RED II and RED III [46]. In this case, the consumption potential ranges from a decrease of 0.2 million tons to an increase of 0.4 million tons. Advanced fuels, on the contrary, are not limited in any way. Likewise, the target levels of their consumption in absolute terms are 4.0–4.5 million tons in case of rejection of the Fit for 55 legislative package and 5.1–5.7 million tons in case of its adoption (current consumption is at the level of 0.6 million tons).

This potential to increase the consumption of biodiesel components from different feedstock sources can be interpreted as a promising free market in the context of the supply of biofuels to EU. In this case, the ongoing campaign in Europe to ban the use of palm oil as a biofuel feedstock is also of significant importance, due to its extremely high

Table 4 Assessment of the potential for increasing the consumption of biodiesel components in accordance with the target structure [55]

From raw materials 1st generation		From UCO and fats		From advanced raw materials		Energy consumption scenario in EU transport sector
2020	2030	2020	2030	2020	2030	
10.0 million tons	10.9 million tons	4.3 million tons	4.7 million tons	0.6 million tons	4.5–5.7 million tons	Scenario –10%
	10.6 million tons		4.4 million tons		4.3–5.4 million tons	Scenario –15%
	10.0 million tons		4.1 million tons		4.0–5.1 million tons	Scenario –20%

ILUC. In the event of a complete ban on this type of raw material in EU, a market volume of more than 2.5 million tons of biodiesel components will be released. This can also be taken into account as further resources for import supplies [62].

The Potential of Raw Material Supply to Produce Biodiesel in Russia

The key raw materials from which the production of FAME and HVO is possible are vegetable oils and animal fats [63]. Specialists are used cooking oil, obtained by collecting and refining household and food industry oils. This also used tall oil, which is a by-product of kraft pulping. The production and consumption of the main types of vegetable oils in Russia varies greatly depending on the region. Consequently, the largest producers are the Central, Volga, and Southern federal districts, which are characterized by the mildest climate and higher specific yields per hectare. Likewise, according to the surplus of the vegetable oil market, the regions of Russia can be conditionally divided into deficit regions, regions with a slight surplus, and regions with a significant surplus. Figure 5. illustrates the surplus of vegetable oils by federal districts of Russian Federation and the values are given in thousand tons [64]. Moreover, the total volume of oil production in the country has been continuously growing for the last four years and is 7.3 million tons in 2020 as can be seen in Fig. 6.

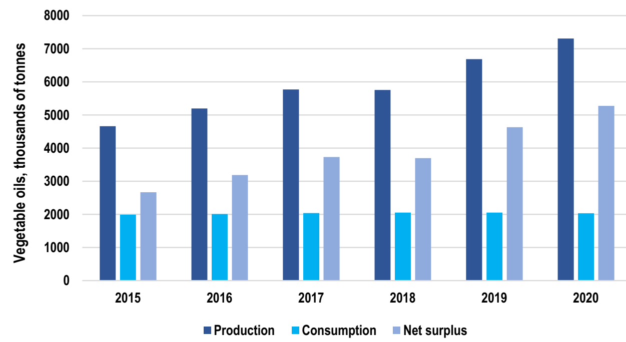


Fig. 6 Balance of production and consumption of vegetable oils in Russia [65]

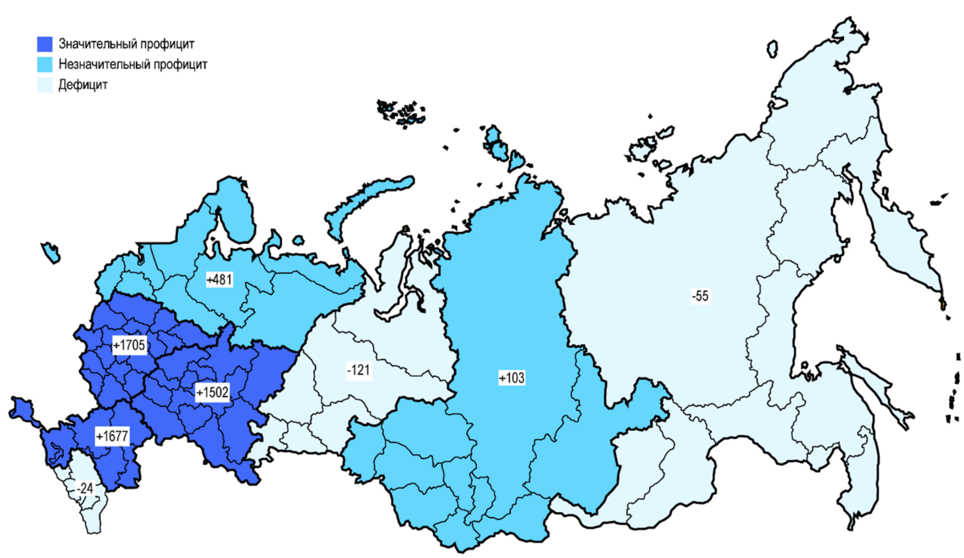
Sunflower Oil

Sunflower oil occupies a large share of the production and consumption of vegetable oils in Russia [67]. The volume of its crude production increased from 4.67 million tons in 2017 to 5.86 million tons in 2020. This is with more than 60% of the production being exported (3.66 million tons in 2020). The largest importers of Russian sunflower oil are China, Turkey, Iran, and India. Despite the developed market, the production of sunflower oil is characterized by the depletion of raw materials, involving the vast majority of areas suitable for growing sunflower are already actively utilized [68]. An increase in harvesting is possible only due to the intensification of cultivation per unit area, involving the utilization of new crop hybrids, improvement of sowing, as well as harvesting schemes, etc. Another obstacle to the use of sunflower oil for biofuel production is a direct conflict with its utilization as a food product, on the basis of which possible local deficits [69].

Soybean Oil

The gross harvest of soybeans has grown 2.5 times over the past 10 years from 1.7 million tons in 2011 to 4.5 million

Fig. 5 Surplus of vegetable oils by federal districts of the Russian Federation and the values are given in thousand tons [65, 66]



tons in 2020) [70]. The current increase is also characteristic of the production of soybean oil, which in 2020 amounted to 811,000 tons, with a significant part of it being exported (663,000 tons). In addition to the increase in sown areas, a significant increase in soybean yields was caused using breeding achievements and intensive production technologies, involving new agricultural practices, crop rotations, etc. [71]. This ensured a high specific yield per hectare [72] s. In 2020, almost half of soybean oil exports 326,000 tons and came from China. Algeria is also an important importer of 22% exports [73].

In Russia, soybean oil is utilized mainly as feed and to a lesser extent utilized as food products. This parameter limits its use as a technical raw material for the production of fuels. At the same time, there are specially bred varieties of oilseeds. These include sunflower and soybeans, which produce High Oleic Low Linolenic (HOLL) [74, 75]. This has increased thermal and oxidative stability. They are considered raw materials for the production of the highest quality in terms of oxidative stability of biodiesel fuels. It is expected that the growth in the production of soybeans and soybean oil in Russia will gradually raise, in particular due to state support in February 2020, and Government Decree No. 86. This approved the procedure for providing and distributing subsidies to regional budgets to stimulate an increase in the production of soybeans and rapeseed [76].

Rapeseed Oil

Over the past 10 years, the gross production of spring and winter rapeseed has almost tripled due to the introduction of new varieties and hybrids on the market, as well as the increasing introduction of intensive cultivation technologies [77]. An important feature of rapeseed is the low indirect change in land use [78]. The crop is cold tolerant and can grow where other food plants cannot grow. Thus, an increase in rapeseed production will not lead to the displacement of valuable crops. This could replace forests and other ecosystems with high specific uptake of carbon dioxide [72]. The absence of this impact can become decisive in the process of recognizing the fuel as sustainable under the European directive RED II**.**

The production of rapeseed oil, as well as the harvest of rapeseed, is actively growing [79]. Even taking into account a slight decrease in 2020, it increased by 1.7 times compared to up to 585,000 tons for 2017. The bulk of rapeseed oil produced in Russia is exported, which in 2020 amounted to about 630,000 tons. The excess of the amount of exported oil over production in the country is also due to the presence of its imports in 2020, where it amounted to 124,000 tons [80]. The key importers of rapeseed oil from Russia are Norway and China in the last few years. These also significant buyers are European countries, such as Latvia, Lithuania, and Netherlands [81].

The production of rapeseed and its free volume in Russian Federation is inferior to those of soybean and, in particular sunflower oil [82]. Nevertheless, in the context of biodiesel production, it has its own advantages. First, since rapeseed is not a food crop in Russia, it will have fewer barriers to becoming a feedstock for biodiesel. There is no conflict of interest between the food and fuel industries. Secondly, rapeseed has great potential to expand crops. A significant increase in crop harvest is possible due to the shift of the main regions of cultivation of winter rapeseed from the Southern to the Central and Northwestern federal districts and the expansion of the acreage of spring rapeseed in the Siberian Federal District. The introduction of spring rapeseed into the soybean crop rotation in the Far East would create a new rapeseed belt from Chita to Vladivostok. Consequently, the total gross harvest of spring and winter rapeseed in the medium term can be raised to 10–15 million tons and raised to 4–6 million tons in terms of rapeseed oil [83].

In the short term, further growth in the production of vegetable oils in Russia is expected. Figure 7 displays the forecast for the production of vegetable oils in Russian Federation. The production of sunflower oils, which occupy the largest market share, continues to grow. Nevertheless, due to the exhaustion of the territories available for sowing, it is characterized by a less significant increase. Rapeseed oil is expected to grow the most due to a significant expansion of acreage, which has the potential to surpass the country's soybean oil production.

Tall Oil

Unlike other types of oils, tall oil is not grain-based, but woody [84]. In the Kraft pulping process, which is executed to extract lignin from wood, black liquor is obtained as a by-product, which is a complex colloidal mixture. Figure 8 illustrates the Kraft process flow diagram. Subsequently, the most valuable component is extracted from it—sulphate soap, from which Crude Tall Oil (CTO) will subsequently obtained, and the rest is evaporated and burned. The output of sulphate soap is about 40 kg/t per dry pulp when processing hardwood and up to 160 kg/t when cooking softwood [85]. To obtain crude tall oil from sulphate soap, it must be decomposed with sulfuric acid. Likewise, the average yield in this process is 405 kg of oil per 1 ton of soap. Additionally, Russia does not maintain official statistics on the production of tall oil. Thus, we calculated its theoretical potential based on the data on the production of sulphate pulp for 2020 [86]. The value of 341.1 thousand tons of crude tall oil or 136.4 thousand tons of tall acids was obtained (subject to full processing in this direction).

For the production of HVO, both fatty acids of tall oils and crude tall oil (even with the addition of tall oil pitch) can be utilized as raw materials. In 2020, the export of CTO, which is an indicator of the production surplus in the country, amounted to 45.4 thousand tons do not exceed 93,000 tons [89]. Where, 37.3 thousand tons of rosin were produced in 2020 and the yield of which is on average 40% per CTO. Thus, most of the tall oils remain unprocessed and are used in their raw form. It can be assumed that domestic pulp and paper mills do not have the opportunity or material incentives to develop a chain of deep processing of tall oil. Thus, the production of biofuels can become a driver of modernization. Moreover, the small share of tall oil processing in Russia makes it a promising feedstock for the production of

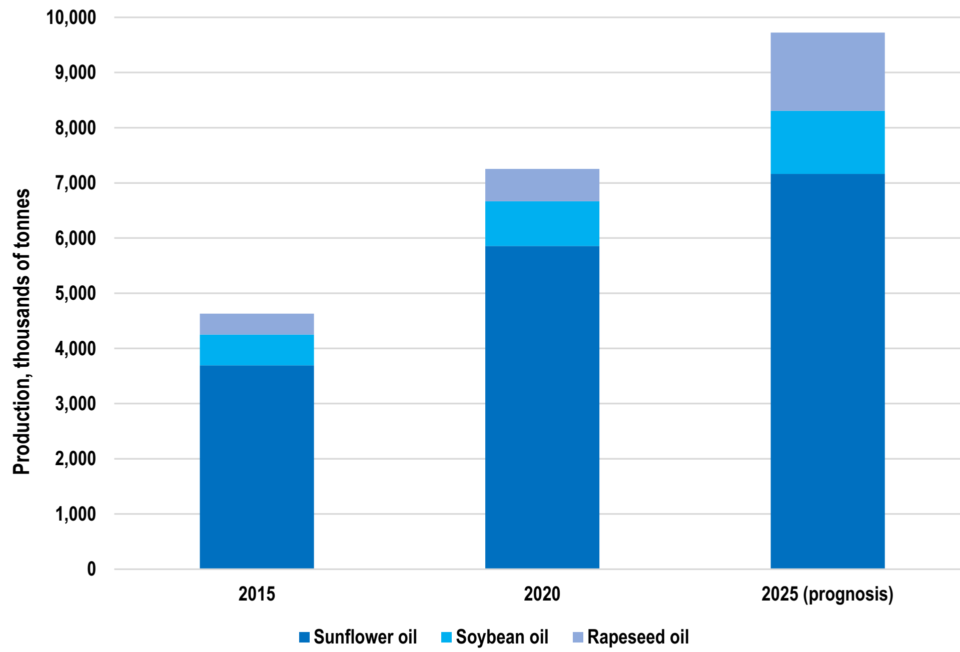


Fig. 7 Forecast for the production of vegetable oils in Russian Federation [66]

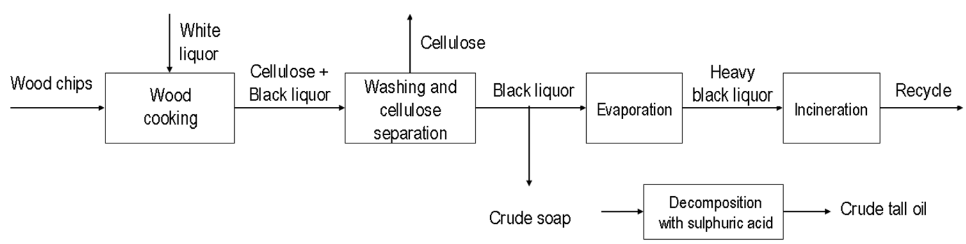


Fig. 8 Kraft process flow diagram [87, 88]

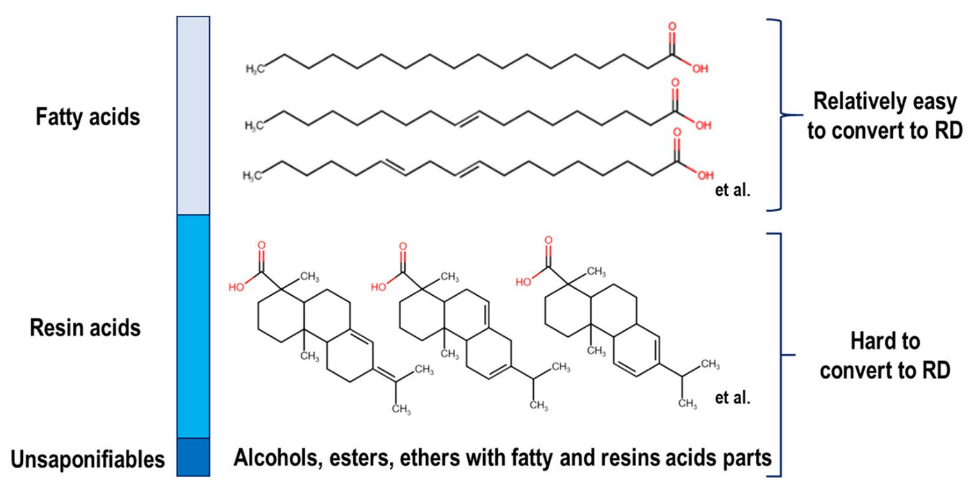


Fig. 9 Chemical structure of CTO components [88, 92]

biodiesel fuel, since the biofuel industry can fill this niche [90]. Taking into account the total volume of CTO production to be more consistent with reality and it was taken in the amount of about 300,000 tons. Figure 9 illustrates the chemical structure of CTO components. The volume of exports is about 45,000 tons, and the volume of already existing processing is about 93,000 tons [91]. Consequently, the raw material base of tall oils for biodiesel production can up to 162,000 tons according to the RED II Directive [46]. Tall oil is one of the raw materials from which it is possible to obtain advanced biofuels. Consequently, it is extremely important to use the full potential of its domestic production.

Used Cooking Oil

Waste cooking oils and used cooking oil (UCO) are commonly referred to as two types of waste, involving professional, and associated with the work of the food industry, containing restaurants, food enterprises, as well as household, related to a single household [93, 94]. The quality of the oil can vary greatly from batch to batch, which is why biodiesel production requires UCO pre-treatment [95]. Figure 10 demonstrates the schematic diagram of biodiesel production for waste cooking oil. In Russia, the waste collection and disposal system are not centralized. Furthermore, official statistics are not kept, and there are only small companies involved in buying up UCO [96]. At the same time, the key direction for the sale of used oils for collecting companies is export abroad, where their cost is higher [97]. In 2020, exports amounted to 80,000 tons, including utilized animal fats. It is most likely that the entire volume of used oils collected in Russia in 2020 is slightly more than this number. Representatives of organizations involved in the collection of oils in Russia note that the number of suppliers and supplies is increasing.

In European Union, the number of UCOs and their production potential are calculated based on the experience of experts and oil collectors, through surveys of market participants [100]. In 2020, the consumption of oils in European Union amounted to about 8 million tons, while the total potential of UCO is approximately 1.15 million tons of used cooking oils [101, 102]. Oil consumption throughout Russia reaches 2 million tons, and the total potential of used cooking oils is 292,000 tons. Additionally, collection of oils throughout Russia from all settlements is impossible [103]. Impractical in terms of the complexity of collection and transportation, when considering the largest cities in the central part Russia's maximum potential can be 100–150,000 tons/year. Table 5 compares the various feedstocks for biodiesel production. Most attractive raw materials are used cooking oils in terms of indicators [104]. However, due to the small volume of their collection, additional raw materials are needed to ensure the scale of the enterprise. Likewise, the most promising of which is rapeseed oil. This set of raw materials in the ratio of 20/80 will be used in further calculations of the economic efficiency of the project [105].

Economic Evaluation of Biodiesel Production in Russia

The calculation model used in this paper is based on the assessment of the cost of key parameters. These affect the cost of the final product, involving the cost of raw materials, as well as the value of the transport component for raw materials and products. Moreover, these impact the capital costs for the preparation and processing of raw materials in HVO process, operating costs for the preparation and processing of raw materials in the HVO process, the cost of by-products and target products, taxes, excises, and duties. The cost of rapeseed oil is based on official data from the Federal

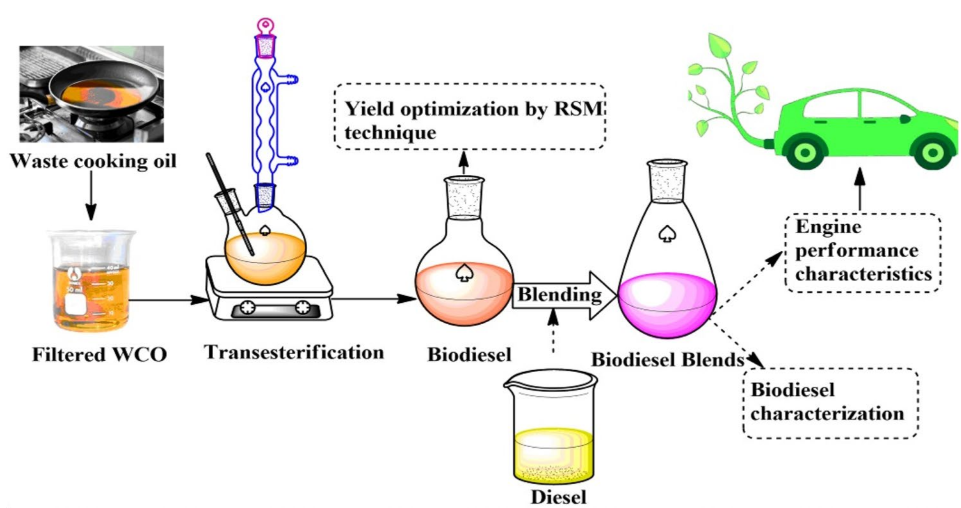


Fig. 10 Schematic diagram of biodiesel production for waste cooking oil [98, 99]

Table 5 Evaluation of various types of raw materials for the production of biodiesel fuels in Russian Federation [33]

Type of raw material	Advantages	Disadvantages
Sunflower oil	The largest volume of production and surplus	The smallest relative growth potential among heavy oils; Exclusive use as food in Russian Federation
Soybean oil	In addition to oil, the culture gives a greater yield of valuable high-protein products, including cake and meal	Low growth potential
Rapeseed oil	The greatest potential for growth due to the inexhaustibility of sown areas	Higher prices and food orientation of rapeseed oil in Europe
Tall oil	The resulting biofuels are advanced	Complexity of preparation and processing; Small volume of production and the impossibility of its growth beyond the potential is about 340,000 tons; The need to develop a chain of deep processing of pulp and paper mill waste
Waste cooking oil an animal fats	Low price; Biofuels will have a very low carbon footprint and an almost zero energy tax rate	Small volume of the market and the impossibility of its growth beyond its potential is about 290,000 tons for used oils

Table 6 Cost of raw materials for calculating economic efficiency, $/t [106]

Type of raw material	Average price for 2021
Rapeseed oil	1077.9
Used cooking oil	969.4

Table 7 Production cost for economic performance calculations [106]

Product	Selling price	Taxes, excises	Retail margin	"Net" price
HVO:				
Sweden	2766.9	553.4	201.2	2012.3
Belgium	3947.8	1630.7	292.6	2024.5
Naphtha	749.7	310.3	0.0	439.4
Propane:	632.9	105.5	0.0	527.4

State Statistics Service. Due to the lack of a formed domestic market for used cooking oils and the predominant export orientation of the existing supplies of this product, the data of the Federal Customs Service were taken as the price for it. The calculation is carried out at average prices for 2021. The prices accepted for analysis are presented in Table 6.

The value of the transport component is calculated on the basis of the existing tariffs for transportation by rail. Moreover, this is also specified taking into account the specifics of transport to Europe, as well as the presence of customs duties. Pure HVO is considered as a product due to the significant difference in the effective selling prices of HVO and petroleum diesel fuel. The availability of information only on the price of a pure biodiesel component, which were taken on two bases in Sweden and in Belgium from sources [107]. Table 7 illustrates the production cost for economic efficiency calculations. When HVO is added to standard diesel fuel, it is much more difficult to calculate its effective price. Since often the involvement of biodiesel is not economically justified and is stimulated by existing mandates. Therefore, the presence of penalties if the target is not met. As a result, the average price of diesel fuel in a certain country is rising due to an increase in the cost of its production, and this applies to both B0 fuels and fuels using biocomponents. This is due to the present production structure, when fuel companies incur additional costs due to the mandatory addition of biocomponents distribute the load equally on all brands of road fuels, such as B0, B7, and B10+. The price for by-products, including naphtha and propane in Russian Federation is based on data on domestic prices in Russian Federation. At the same time, it is obvious that these products, due to their "green" origin will be able to find ways to sell at a higher price. However, due to the low yield, it was decided not to take into account this price difference.

The calculation of capital costs was executed according to the methodology set out in ASTM manual [15]. The unit costs obtained in accordance with this methodology were adjusted for inflation and for the regional factor associated with consistently higher prices for similar units in Russia compared to United States. Operating costs were calculated based on publicly available cost figures for various processes set out in a number of handbooks, manuals, and white papers. It should take in the consideration current prices for energy resources, labor, as well as auxiliary reagents. For stand-alone plants, capital and operating costs were calculated using the methods mentioned without modification.

In the case of joint processing, additional costs are implied that arise when upgrading a conventional diesel fuel hydrotreatment unit by 2 million tons/year with an increase in its capacity. Furthermore, this is with adding a hydroisomerization reactor to the scheme for an oil capacity of 100,000 tons/year. The hydroisomerization reactor was not taken into account due to the assumption that such a small amount of normal paraffins. As a results, these could not significantly affect the low-temperature properties of blended diesel fuel.

An extremely important indicator is also the material balance of the oil hydroprocessing process. This is determined by the ratio of the rates of hydrodeoxygenation and decarboxylation reactions, as well as the degree of raw material degradation. It is carried out under conditions of 100% conversion of triglycerides and fatty acids. In the current article, hydrogenation is chosen as the dominant way of removing oxygen. Consequently, the amount of feedstock reacting with the elimination of a carbon atom is fixed at 10%. Destruction is also limited to a low value of 5% from the amount of paraffins obtained at the stage of hydrodeoxygenation. The final yield of HVO with these indicators is 81.58%, which is consistent with the existing data on the yield of the biodiesel component at Neste plant in Singapore [108]. To analyze the impact of capacity on the economic performance of production, two plant options were selected, including 100,000 and 500,000 tons/year. This is approximately consistent with the existing capacities in the world. The results of calculating the economic efficiency of HVO production for various options, involving a capacity of 100,000 and 500,000 tons/year in the format of a separate unit and combined production are presented in Table 8.

Among the studied options, the only economically inefficient one is with a capacity of 100,000 tons/year when produced at a separate installation. The remaining production schemes are characterized by approximately similar payback and profitability indicators. Therefore, in order to make a reasonable choice of the most promising of them, it is necessary to turn to non-monetizable advantages:

Possibility of SAF production as individual units is much more flexible in terms of manufactured products. Since a slight change in process conditions and type of catalyst can significantly change the final material balance of the process and increase the yield of HEFA. In joint processing, the operating mode is tied to the hydrotreatment of petroleum diesel, and the separation of kerosene fractions from the hydrogenate after upgrading is not advisable. In this calculation, this factor is partially taken into account due to the presence of HEFA in the list of marketable products, as well as setting a price for it 10% higher compared to HVO. This made it possible, in the case of a capacity of 500,000 tons/year, to recoup the higher capital costs of a separate plant and align the indicators of the investment project. At the same time, potential flexibility remains a non-monetizable advantage;

Greater flexibility in terms of manufactured products during joint processing, the entire volume of the biocomponent will obviously be mixed with diesel fuel in a certain and approximately constant concentration. This means that it will not be possible to sell it separately and vary the HVO content depending on the market. In the current environment, when selling biofuels for export is economically profitable and the domestic consumption is not profitable, this flexibility is an extremely important advantage.

Thus, taking into account the existing advantages and calculated indicators of economic efficiency, the most preferable option is the hydroprocessing of oils in a separate unit with a capacity of 500,000 tons/year for oil. Large capacity is probably redundant given the limited resources of advanced raw materials up to 100–150,000 tons of waste oils and up to 150–200,000 tons of tall oils.

Conclusion and Policy Implications

One of the most decisive fuels for substituting petroleum fuels is biodiesel. It is a clean and renewable and sustainable energy that can affect positively the atmosphere. The most promising low-carbon component of biological nature is hydrotreated vegetable oils (HVO). This has higher calorific value, and greater chemical stability than FAME. A separate advantage is the absence of blending restrictions

Table 8 Economic performance of various HVO production schemes [106]

Installation configuration option	CAPEX, million $	OPEX, million $	IRR, %	DPP, year	Economic efficiency	Perspective produced by SAF
Separate processing 100,000 tons/year	120.0	5.4	25.9	9.6		
Separate processing 500,000 tons/year	291.1	21.8	45.4	5.5		
Joint recycling 100,000 tons/year	62.6	4.1	45.1	5.7		
Joint recycling 500,000 tons/year	268.0	24.5	45.1	5.6		

and the ability to obtain a sustainable aviation fuel (SAF) with the right raw materials. The greatest influence on the development of biodiesel production in the world as a whole and especially in Europe is the adoption of regulations aimed at stimulating their growth.

Russia has launched the process of developing low-carbon strategies for the energy transition, but the country is placing more emphasis on the electrification and gasification of transport. At the moment, the foundations of the future carbon regulation system are only being laid. At the same time, insufficient attention is paid to the topic of transferring transport to biofuels. The most promising feedstock for biodiesel production in Russia is rapeseed oil, as rapeseed retains a higher yield growth potential. Moreover, this has low indirect land use change, and the fuel produced from it is more likely to be recognized as advanced. Although Sunflower and soybean oils have a developed market for production and consumption, as well as they are also exported in significant volumes, they unpromising for the production of biodiesel fuel. This due to their exclusive food orientation in Russian Federation. Consequently, problems with federal authorities may arise during the implementation of the project executive branch representing the agricultural sector.

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest The authors declared that there is no conflict of interest in this work.

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