Research Article

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OPTIMISATION OF AGRICULTURAL CROP ALLOCATION IN SUSTAINABLE BIOFUEL PRODUCTION AND ENERGY SECURITY STRATEGIES

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Background. Energy and food security, as well as resilience to climate change, are key priorities in development strategies. Increasing prices of conventional energy resources and their uneven distribution across countries are major drivers of the development of renewable energy sources. The production and use of biofuels play a crucial role among renewable energy sources, reducing dependence on imported conventional fuels and creating new employment opportunities.

Purpose. This study aims to develop scenarios for the production and consumption of liquid biofuels in Ukraine to increase energy security and ensure sustainable development.

Findings. The production of liquid biofuels revealed that leading countries producing bioethanol and biodiesel often have traditional energy sources but are diversifying their energy portfolios. An algorithm for choosing between the food and energy use of crops was proposed, based on key selection criteria such as the level of domestic crop provision, the level of national energy security, and the efficiency of using crops for energy purposes relative to exports. This study identified the potential for bioethanol and biodiesel production in Ukraine based on export scenarios. This demonstrates Ukraine's potential to meet its needs and export finished bioenergy products (biofuels) to European and global energy markets. Three comprehensive scenarios for the production and consumption of biofuels in Ukraine up to 2035 were developed with target indicators for the substitution of traditional fuels at levels of 6%, 12% and 20%, respectively. The required areas for sowing optimal crops (wheat (20%), corn (40%), sugar beet (40%) for bioethanol and rapeseed (100%) for biodiesel) were calculated. To achieve the target indicators, these areas will amount to 1.8%, 3.6%, and 5.9% of the average crop area in Ukraine in 2020-2023, which demonstrates that biofuel production will not threaten food security.

Implications. Agricultural crop distribution for sustainable biofuel production and energy security strategies can serve as the basis for Ukraine's long-term national bioenergy policy, thereby increasing energy security and achieving climate goals. Implementing integrated scenarios will require allocating the necessary cropping areas, but the analysis indicates this will not threaten food security.

Keywords: Biofuels, Bioethanol, Biodiesel, Food Market, Energy Security, Crops.

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1. Introduction.

Food and energy security and climate change remain key to public policies and development strategies that focus on the efficient use of national resources, ensuring sustainability, and rational planning (Georgescu et al., 2025). Today, the energy security and climate sustainability of many countries require the greater use of renewable energy sources (RES). This is because conventional energy resources are unevenly distributed across countries, most countries are importers and depend on energy market conditions, and conventional energy sources will be depleted, leading to rapid price increases.

The adoption of the European Green Deal (European Union, 2019) is an important indicator of the EU's approval of its strategic course for ecological transformation, energy independence through RES, and sustainable development. The European Green Deal is a roadmap for transforming Europe into the world's first climate-neutral continent by 2050 (Honcharuk et al., 2024).

The REPowerEU Plan (European Commission, 2022), adopted by EU countries in May 2022, is a package of measures aimed at rapidly reducing the EU economy's dependence on conventional energy sources. The plan is to be implemented by accelerating the clean energy transition, consolidating efforts to create a sustainable energy union, and building a sustainable energy system through diversification of energy suppliers, as well as energy efficiency and energy saving measures.

Increasing the use of RES, particularly biofuels, is a key factor in the clean energy transition, reducing dependence on fossil fuels, and supporting economic development in developing countries. Domestic production of biofuels involves creating new enterprises within the country, which will allow it to fill its budget with taxes; activate mechanical engineering to provide enterprises with equipment produced domestically; create new "green" jobs; and improve the country's balance of payments by reducing imports of conventional fuels. For the qualitative development of biofuel production and consumption, countries must provide a strategic vision for industry development.

Elaborating on practical scenarios for the development of bioethanol, biodiesel, and other biofuels is also important. This study aims to develop scenarios for the production of biofuels (bioethanol and biodiesel) in Ukraine to help define strategic directions for the industry's development at the state level. The research questions (RQs) set in this study are as follows:

RQ1. Justification of the algorithm for selecting crop directions, with specifications of baseline scenarios (food/energy use).

RQ2. Study of the current state of bioethanol production and consumption in the world and Ukraine, as well as the development of scenarios for the growth of the Ukrainian bioethanol industry.

RQ3. Analysis of the state of the biodiesel industry in Ukraine and the world market for this type of biofuel, with the development of scenarios for growth in Ukraine.

RQ4. Development of complex scenarios (pessimistic, realistic, and optimistic) for the production and consumption of liquid biofuels (bioethanol and biodiesel) in Ukraine, with justification of target indicators for replacing conventional fuels.

RQ5. The required crop area for biofuel production was calculated based on comprehensive scenarios for the production and consumption of liquid biofuels in Ukraine.

2. Literature Review.

European countries and other advanced nations worldwide are taking numerous steps to decarbonise their economies, and RES development is one way to achieve this goal. According to the European Environment Agency (EEA), the share of RES in total energy consumption in the EU increased from 10.2% in 2005 to 24.0% in 2023 (EEA, 2024). The importance of renewable energy sources, particularly biofuels, is increasing. Deora et al. (2022) argue that biofuels and biomass are the only RES capable of replacing conventional fuels to achieve future targets, as they are environmentally friendly and inexhaustible. In their review of bioenergy development and biofuel production, Singh et al. (2022) noted that lower biofuel production costs than those of conventional fuels are another important advantage.

Okhota et al. (2024) studied the contribution of bioenergy to reducing environmental risks and implementing sustainable solutions in rural communities, using Ukraine as an example.

Yılbaşı (2025) reviewed biofuels, electrofuels, and fuels obtained from waste and outlined their respective characteristics. This enabled the identification of strategic prospects for industry development, including the need to intensify scientific research into the production of first-, second, and third-generation biofuels.

Bai et al. (2012) and Pydimalla et al. (2023) examined the potential of crops for biofuel production, in particular biodiesel, covering both feedstock and technological aspects. Mignogna et al. (2024) studied the use of biomass for energy purposes across different countries. A bibliometric analysis of the potential of biomass for biofuel and energy production by Sertolli et al. (2022) confirmed the relevance of this research area and the interest in developing biofuel production technologies across different countries. However, such studies are currently insufficient in Ukraine. Most of them focus on analysing the feedstock base for the production of specific types of biofuels (Koval et al., 2025; Lohosha et al., 2025). There is a need for a comprehensive study of the potential to optimise crop distribution for energy purposes within the framework of sustainable biofuel production.

It is also important to forecast the biofuel industry's development at different levels, enabling the development of strategic measures to stimulate the most promising areas of bioproduction. Wulff et al. (2025) proposed four scenarios for long-term fuel demand. According to the results, each predicts that the demand for renewable fuels will grow rapidly in 2030-2040.

The global biofuel production and development scenario proposed by Guo (2020) predicts that by 2050, biofuels will account for 27% of the world's liquid transportation fuel supply. In Ukraine, the development of biofuel production scenarios is becoming increasingly relevant under martial law. The implementation of these measures can significantly strengthen energy security, ensuring the stability of energy supply, and reducing dependence on imports of conventional energy carriers.

Existing scenarios for biofuel production and consumption in Ukraine (Geletukha et al., 2023; Kaletnik & Pryshliak, 2021) generally focus only on the projected share of liquid biofuels in the total motor fuel consumption and the corresponding production volumes. This study will be more comprehensive, accounting for different crop uses and export options for both feedstock and finished bioenergy products. Scenarios for specific types of biofuels and different options for integrated scenarios (bioethanol and biodiesel) will also be developed.

3. Methodology.

3.1. Conceptual Framework and Algorithm.

The first stage of the methodology was to determine the object, subject, and research area, and to develop the hypotheses. The objective of this research is to study the production and consumption of liquid biofuels produced from crops. This research focuses on the potential for biofuel production from agricultural feedstocks and on its possible uses. The research area includes Ukraine. To determine the prospects for the development of the industry in Ukraine, the global experience in producing liquid biofuels (bioethanol and biodiesel) was analysed.

The research hypothesis is that Ukraine can implement three types of scenarios for the development of the biofuel industry (pessimistic (S_1), realistic (S_2), and optimistic (S_3), and each one will provide for a mandatory share of biofuels in the total consumption of motor fuels, which corresponds to the global trends; at the same time, it causes no threats to food security.

The criteria for assessing crop potential for implementing scenarios for the energy and food use of agricultural crops, according to the authors' algorithm, are as follows:

1. The level of crop self-sufficiency within the country (an indicator characterising the extent to which domestic consumption of the crop is covered by domestic production) is determined by threshold values such as a low level of less than 100% and a high level of more than 150%.

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2. The level of energy security in the country (based on the analysis of the extent to which energy needs are covered by domestic production); threshold values: low level – 50-60% or less; high level – more than 80%.

3. The efficiency of using the crop for energy purposes compared to exports (estimated by comparing the profit from exporting 1 ton of the crop with the profit from selling biofuel produced from 1 ton of the crop (the volume of biofuel is equated to the volume of the corresponding type of conventional fuel); threshold values: low level – profit from energy use is equal to or lower than profit from exports; high level – profit from energy use is higher than profit from exports by ≥20%.

3.2. Analytical Base and Data Sources.

The study uses open statistical data related to the development of the biofuel industry (OECD/FAO Agriculture Statistics (database), data provided by the State Statistics Service of Ukraine), analytical materials, in particular, the Global Bioenergy Statistics Report provided by the World Bioenergy Association, as well as analytical data from the Ukrainian Analytical Center "Pro-Consulting".

The initial data for calculating the energy potential of crops (biofuel yield per unit area) were based on materials from the Bioenergy Association of Ukraine and on practical experience in processing rapeseed into biodiesel at Vinnytsia National Agrarian University. When calculating the costs of biofuel production and conventional fuels, data from the State Statistics Service of Ukraine, the Bioenergy Association of Ukraine, and our own calculations were used.

3.3. Research Design.

The research sequence is illustrated in Figure 1. The development of the relevant scenarios involved the use of the authors' algorithm for choosing between food and energy use of agricultural crops, trends in the global development of the biofuel sector, the results of the analysis of the current state of bioethanol and biodiesel production in Ukraine, and the authors' methodology for determining the ratio of bioethanol and biodiesel in the target indicators of replacing conventional fuels with biofuels in optimistic, realistic, and pessimistic scenarios for Ukraine.

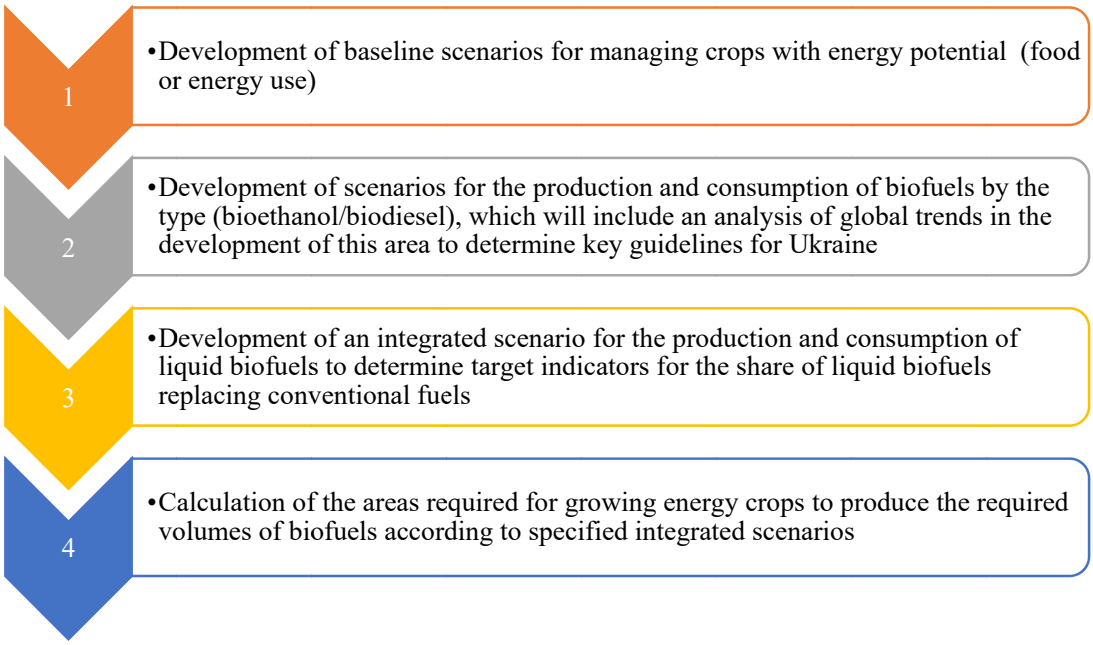

Fig. 1. Research Sequence (Design).

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To assess the probability of implementing the scenarios (Tables 1 and 2), an expert method (expert assessment) was used. The panel consisted of senior academic experts with doctoral qualifications from Vinnytsia National Agrarian University in the field of biofuel production, as well as university stakeholders. When assessing the scenarios, they considered the current state of biofuel production in Ukraine and the potential for industry development, as well as Ukrainian and European regulatory documents.

3.4.Scenario Forecasting and Probability Assessment.

The methodology for calculating the required volumes of biofuel production for each scenario involved:

1. The target share of biofuels in the total use of fuels (a), which determines the level of substitution of conventional fuels in the transport balance, is as follows:

- Pessimistic scenario: a_1 = 0.06 (6%);
- Realistic scenario: a_2 = 0.12 (12%);
- Optimistic scenario: a_3 = 0.20 (20%).

When selecting target indicators, we were guided by domestic and European regulatory frameworks, with adjustments to accelerate European integration in Ukraine. For the pessimistic scenario, the target indicator (6%) is based on the norm of at least 5% biocomponents in liquid fuel set by the Verkhovna Rada of Ukraine (2024). When developing the target indicator for the realistic scenario, which provides for a 12% share of biofuels, the target of the "Energy Strategy of Ukraine until 2035" (Cabinet of Ministers of Ukraine, 2017) was taken as the basis: 11.5% of primary energy supply from biomass, biofuels, and waste, which can be applied to the transportation sector. The optimistic scenario assumes a 20% substitution of conventional fuels with biofuels, which aligns with the European norm of 29% renewable energy in transport by 2030, as set out in RED II (European Union, 2023).

2. The structure of biofuel replacement meets the strategic guidelines for bioenergy development, with lower priority given to bioethanol (30% of all biofuels) and higher priority given to biodiesel (70%).

This division is explained by the fact that biodiesel is more widely used, particularly in the agricultural sector, where diesel fuel accounts for approximately 70% of consumption (State Statistic Service of Ukraine, 2025), and the agricultural sector generates the budget of Ukraine.

The share of bioethanol (b) in the overall biofuels structure is $b_{bioeth.}$= 0.3, and the share of biodiesel $b_{biodies.}$ = 0.7.

The shares of bioethanol and biodiesel in each scenario were as follows:

$$a_{bioeth} = a \text{ x } b_{bioeth}$$
$$a_{bioedies} = a \text{ x } b_{biodies} \quad (1)$$

To calculate the volumes of biofuels in physical units for each type (Q), which will be mixed with conventional types of fuels, calculations were made based on the total consumption of motor fuels ($Q_{tot).}$ The volumes of actual fuel consumption on average for five years in Ukraine will be taken as the basis, according to statistical data (State Statistic Service of Ukraine, 2025), which is 9 million tons. The calculation for individual types of biofuels is as follows:

$$Q_{bioeth} = Q_{tot} \text{ x } a_{bioeth} \quad (2)$$

The next step involved calculating the area required to grow crops for biofuel production to meet the target benchmarks defined by the developed scenarios.

3.5. Assessment of the Probability Scenarios and Limitations.

Assessment of the probability scenarios was conducted using an expert method, considering the available statistical data on the development of the biofuel industry, modern achievements in science and technology, and steps announced by Ukraine to reduce energy dependence by stimulating biofuel production.

Methodological limitations relate to the availability and quality of input information, as well as possible changes in the institutional environment associated with martial law. The assessment completion includes generalising the data obtained and forming conclusions and recommendations on the selection of optimal scenarios for Ukraine.

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4. Results.

Currently, first-generation biofuels dominate the global production. Its feedstock includes traditional food crops, among which starch crops (corn, grains), sugar crops (sugar beets, sugar cane), and vegetable oils (in particular rapeseed and soybeans) remains popular (Fig. 2).

According to the OECD forecast for 2034, no significant changes in the choice of feedstock base are expected across countries. Nevertheless, the share of waste oils and fats, as well as other feedstocks for bioproduction, is predicted to increase. The development of the biofuel production sector in the medium term is limited by the need to prioritise food security.

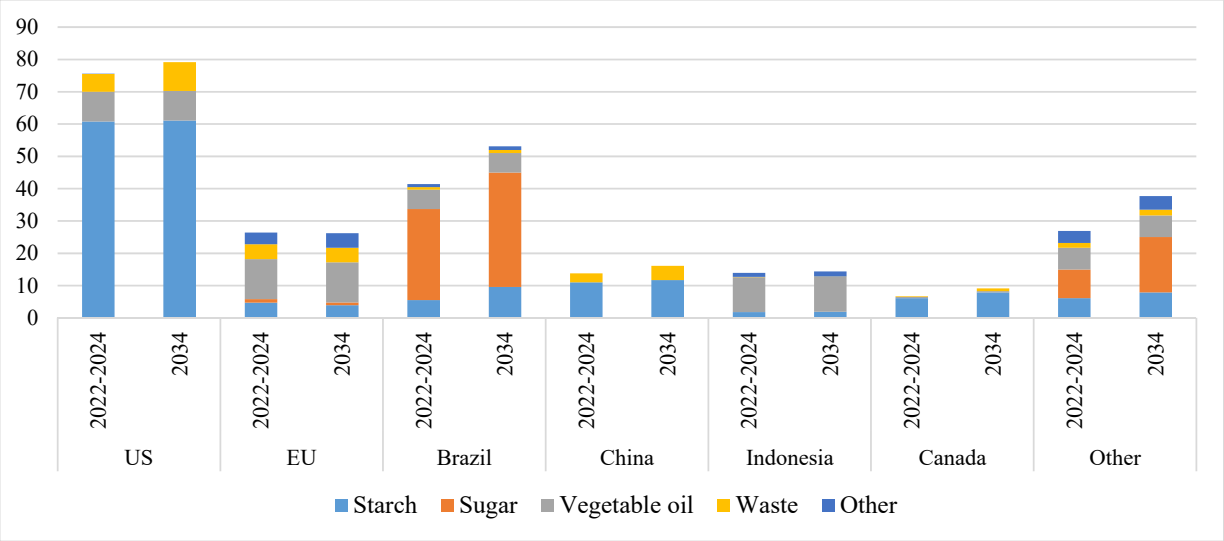

Fig. 2. Global Biofuel Production by Feedstock, 2022–2024 and 2034 Forecast (billion litres).

Source: based on OECD/FAO (2025).

Within each country, the types of feedstock suitable for biofuel production must be reviewed. An algorithm was developed to select baseline scenarios (food/energy use) for crop management at the national level (Fig. 3). Its use at the macro level can serve as a basis for developing state-level policies to stimulate biofuel production from specific feedstocks.

The algorithm for selecting baseline scenarios for crops with bioenergy potential is based on sequentially selecting more effective alternatives. The algorithm begins by selecting an agricultural crop grown in the country that can be used for biofuel. The country's food security remains a priority; therefore, the first choice is based on an analysis of the domestic production of this crop. A low level of self-provision leads to the use of domestic food for domestic purposes. This will avoid additional imports and help ensure food security in the country.

A high level of self-provision of agricultural crops suggests potential use for energy purposes. The next step is to analyse the country's energy security. A high level indicates that there is no urgent need for biofuel production within the country, and the agricultural crop (or its processed products) can be sold in external food markets. If energy security is low, it is worth considering the use of agricultural crops for energy.

A high level of domestic crop production and a low level of energy security indicate that it is necessary to assess the efficiency of using crops for energy production. Simultaneously, this was compared with the efficiency of exporting crops. For this purpose, the energy potential of the crop was considered (biofuel yield per ton of feedstock and per unit of area), and the production costs of biofuels derived from it were calculated and compared with those of conventional fuels.

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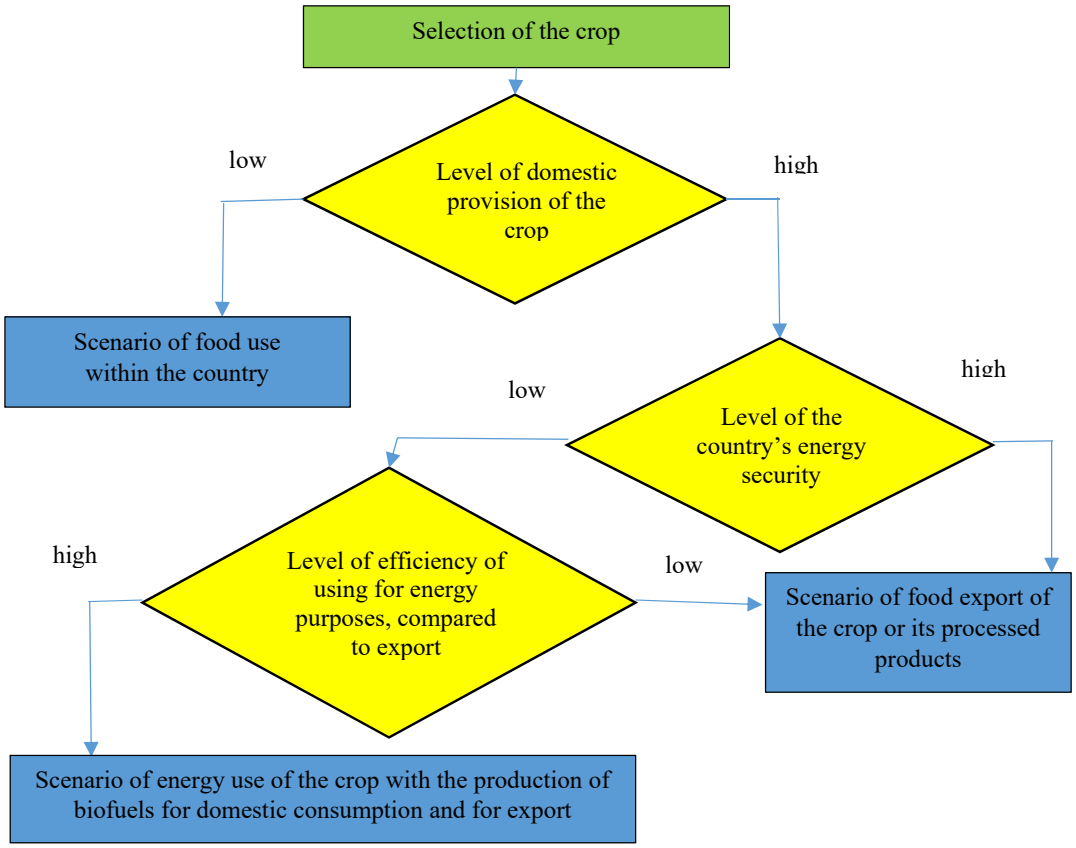

Fig. 3. Algorithm for Selecting Scenarios of the Crop Use at the Domestic Level (Food/Energy Use).

If the crop's domestic energy-use efficiency is low, priority is given to its export or the export of its processed products. A high level of efficiency indicates the feasibility of developing a scenario for the energy use of agricultural crops by processing them into biofuels. Within the country, it is advisable to stimulate further domestic use of biofuels. However, in the event of a surplus, biofuels should be sold in external energy markets.

Today, many countries around the world choose scenarios for the energy use of agricultural crops. Notably, biofuel production and consumption are developing in both countries that lack their own conventional energy resources and those that are self-sufficient. Thus, the United States and China rank among the top five producers of bioethanol and biodiesel (Fig. 4a,b).

Brazil and the USA are the global leaders in bioethanol production. In 2023, their share of production was 80%. EU countries ranked third for a long time; however, in 2023, they ranked fourth, having been overtaken by India. China ranks fifth in bioethanol production (World Bioenergy Association, 2024).

Corn is the primary crop used for bioethanol production in the USA. In Brazil, bioethanol is primarily produced from sugarcane. Low cultivation costs enable Brazil to produce competitive bioethanol. EU countries use a wider range of crops for bioethanol production, including wheat, corn, and sugar beet. At present, interest in second-generation bioethanol produced from non-food feedstocks (straw, corn cobs, and other cellulosic feedstocks) is growing due to the need to reduce competition between biofuel production and the use of crops for food.

The advantages of second-generation bioethanol include the absence of a burden on food security and low feedstock costs. Its key disadvantage is the high cost of the finished product, driven by the high cost of the technological process for converting lignocellulosic feedstock into biofuels.

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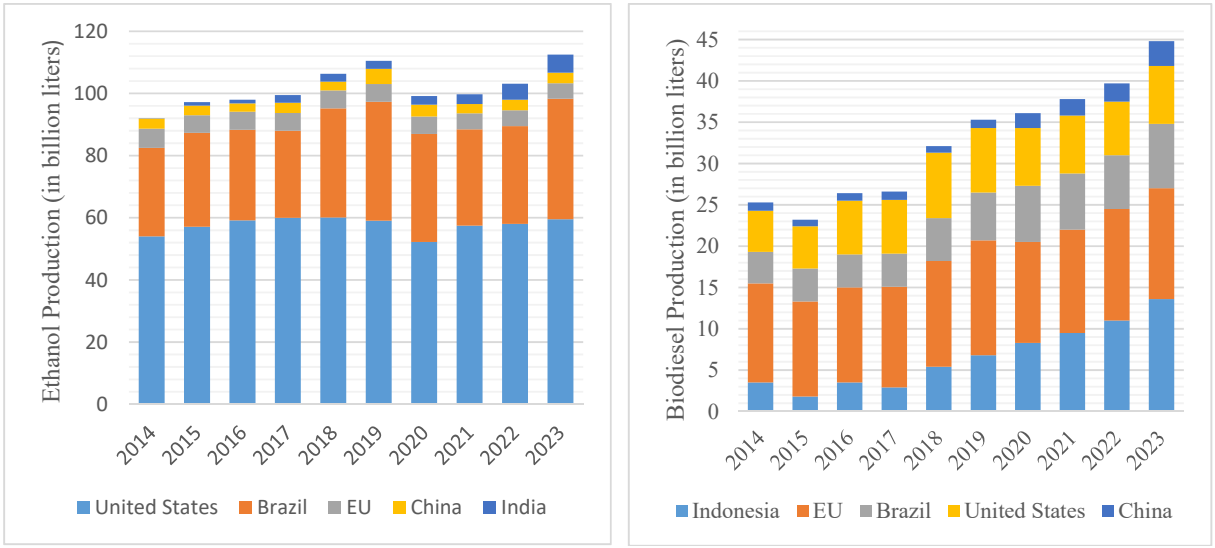

(a) (б)

Fig. 4. Top Five Countries by the Production of Bioethanol (a) and Biodiesel (b) and Their Production Volumes, 2014-2023.

Source: according to the World Bioenergy Association (2024).

The global biodiesel production in 2023 was approximately 50 billion litres (World Bioenergy Association, 2024). Indonesia ranked first, with 14 billion litres, or 28%, of the total volume. Palm oil is primarily used as a feedstock. EU countries ranked second, with 13 billion litres of biodiesel (26%) produced from rapeseed oil and used cooking oil. Brazil ranked third, producing 8 billion litres of biodiesel, mainly from soybeans.

Most countries worldwide have target indicators for the share of bioethanol and biodiesel in total fuel consumption, which are set out in the relevant regulatory documents (for example, EU countries are guided by the RED II Directive, China by the E10 Fuel Policy, and Brazil by the National Biofuels Policy – RenovaBio).

The global market for both bioethanol and biodiesel is growing steadily, driven by state incentives for the industry, quotas for their use, rising environmental standards (particularly goals to reduce CO_2 emissions), advancing technologies, and lower production costs. Another important factor in the growth of the role of biofuels is the destabilisation of the energy market due to Russia's full-scale invasion of Ukraine.

In Ukraine, the bioethanol production industry began to develop actively in 2007, and some existing alcohol plants were equipped with dehydration and denaturation equipment under the ethanol program. Subsequently, sugar factories began installing bioethanol production lines, and specialised plants for its production also emerged. As of 2020, 24 mini-plants for bioethanol production were operating in Ukraine, with a total capacity of up to 500 million litres per year. In 2022, there were fewer than 20 such companies (Pro-Consulting, 2025).

When the full-scale invasion of Ukraine started, the need to introduce a mandatory share of biocomponents in gasoline was justified, which led to the revival of the industry and an increase in bioethanol production (Fig. 5).

Currently, bioethanol consumption in Ukraine is low (1.8-2.3% of the total fuel) (State Statistics Service of Ukraine, 2025). It is expected that, after the introduction of liability for non-compliance with the mandatory bioethanol content in gasoline, domestic consumption will grow rapidly, and the domestic bioethanol market capacity will reach 80 thousand tons per year (Pro-Consulting, 2025).

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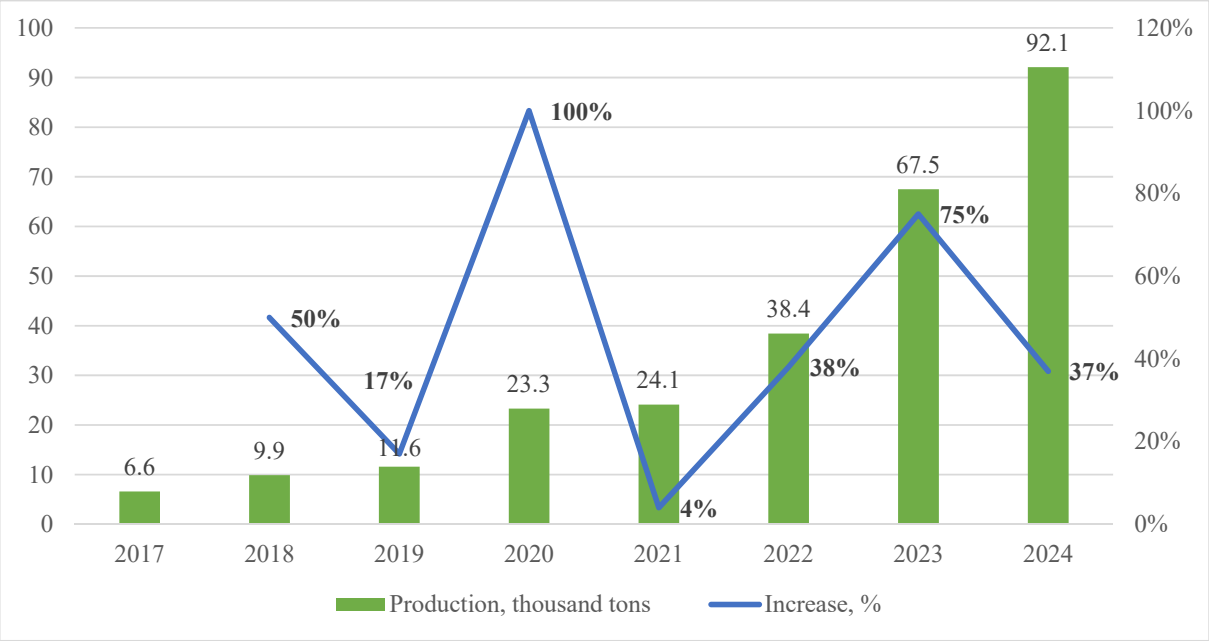

Fig. 5. Dynamics of Bioethanol Production in Ukraine, 2017-2024, Thousand Tons and Annual % Change.

Source: based on Pro-Consulting (2025) and State Statistic Service of Ukraine (2025).

When developing possible scenarios for bioethanol production, it was considered that Ukraine might produce only feedstock for bioethanol production and sell it on foreign markets, stimulate bioethanol production at enterprises of various types (actually specialised in bioethanol only, alcohol, and sugar factories); the products might be consumed within the country; and bioethanol production might be developed for foreign bioenergy markets (Table 1).

Table 1. Scenarios for Bioethanol Production and Consumption in Ukraine.

Scenario	Scenario implementation	Probability of implementation
Scenario oriented towards feedstock export	Ukrainian agricultural enterprises remain producers of feedstock for biodiesel production only (sugar beet, corn, grain crops), and products are exported; bioethanol production is not developed within the country.	low
Scenario focused on the domestic consumption of bioenergy products	Bioethanol is produced at retrofitted distilleries and intended for domestic consumption	medium
	Bioethanol is produced at sugar factories retrofitted with biofuel production lines from sugar beet by-products; bioethanol is consumed within the country.	medium
	Bioethanol is produced at specialized enterprises, usually small, and sold on the domestic market.	medium
Scenario focused on the export of bioenergy products	Bioethanol is produced at all types of enterprises (specialized, distilleries, sugar factories); finished bioenergy products are sold on external energy markets.	low
Scenario of partial use of bioenergy products within the country and partial export	Bioethanol is produced at all types of enterprises; part of it is used domestically to meet the mandatory biofuel share in final consumption of motor fuels, while the surplus is sold on external energy markets.	low

The probability of an export-oriented feedstock scenario was the lowest, as it was associated with the development of the bioethanol sector in Ukraine, the presence of domestic bioethanol plants, and the need to meet domestic demand for this type of biofuel.

The probability of implementing a scenario that combines bioethanol production across various enterprises and its subsequent use both within Ukraine and for export is high.

The introduction of a mandatory share of biocomponents in motor fuels and the high demand for bioethanol in external energy markets will facilitate this process. The Ukrainian biodiesel industry has developed more slowly, and the first biodiesel plant, which used rapeseed, was built by Bio Company Raps (Germany) in 2000. In 2006, the development of biodiesel production was adopted to stimulate the biodiesel industry (Cabinet of Ministers of Ukraine, 2006). According to Pro-Consulting (2025), 14 large biodiesel production plants (totalling up to 300 thousand tons/year) have been built in the country. The introduction of an excise tax on biodiesel and its subsequent growth led most of these plants to stop or be re-equipped to produce other products. Only small plants with a total capacity of up to 25,000 tons of biodiesel per year continued to operate.

In 2019, these plants produced 70,000 tons of liquid biofuel (bioethanol and biodiesel) (State Statistics Service of Ukraine, 2025).

Ukraine remains primarily a producer of rapeseed as a feedstock. However, palm oil processing into biodiesel in the country is insignificant. European markets offer a high price for rapeseed, so farmers export it and spend the proceeds on conventional fuel.

To stimulate rapeseed processing in Ukraine, including for biodiesel, amendments to the legislation were adopted by the Verkhovna Rada of Ukraine (2025). They introduced a 10% duty on rapeseed exports to improve the specific provisions of the tax legislation. Most rapeseed producers believe that such innovations will not stimulate rapeseed processing within the country; instead, they will lead to a decrease in the volume of crop cultivation.

In Ukraine, possible scenarios for the development of biodiesel production depend on various factors, including state policy on export restrictions, crop rotation regulations, and the development of the investment climate.

Using the expert method, four scenarios for biodiesel production in Ukraine were developed based on combinations of these factors (Table 2).

Table 2. Scenarios for Biodiesel Production and Consumption in Ukraine.

Scenario	Scenario implementation	Probability of implementation
Scenario oriented towards feedstock export	Ukrainian agricultural enterprises remain producers only of feedstock for biodiesel production (mainly rapeseed), and products are exported, but biodiesel production is not developed within the country.	high
Scenario focused on the domestic consumption of bioenergy products	Agricultural enterprises are united into energy cooperatives, cultivate feedstock, independently process it into biodiesels, and consume it within the cooperative	medium
	Agricultural enterprises diversify their activities, cultivate feedstock, and independently process it into biodiesel. Both individual consumption and domestic market sales take place.	low
	Agricultural enterprises cooperate with biodiesel producers on a contractual basis, supplying them with feedstock; finished products are sold on the foreign market.	medium
Scenario focused on the export of bioenergy products	Agricultural enterprises cooperate with biodiesel producers on a contractual basis, supplying them with feedstock; finished products are sold on the domestic market.	low
Scenario of partial use of bioenergy products within the country and partial export	Biodiesel is produced from agribusiness's feedstock in Ukraine. Part of the finished products is sold on the domestic market to ensure compliance with the mandatory biofuel share in the final consumption of motor fuels. The surplus is exported to foreign energy markets.	medium

1. The export-oriented scenario assumes that Ukraine will remain a feedstock supplier, particularly for Europe, and will sell only feedstock for biofuel production in external markets.

2. The scenario focused on domestic consumption, which would provide for the production of biodiesel within Ukraine under various organisational schemes: (i) production and consumption directly by agricultural enterprises, (ii) production and consumption of biodiesel within bioenergy cooperatives, and (iii) cooperation of agricultural enterprises with specialised enterprises for the production of biodiesel on a contractual basis for the feedstock supply.

3. The scenario focused on the export of bioenergy products, so that Ukraine would become a full-fledged player in the global biodiesel market.

4. Scenario, involving partial domestic use of biodiesel and partial export, and combining different ways of consumption, both within the country and abroad.

Given the current challenges in the Ukrainian biodiesel industry, an export-oriented feedstock scenario is likely to be implemented. However, with a well-planned state policy to stimulate the industry, it is possible to shift toward domestic production of bioenergy products to meet national needs and exports.

Initiatives regarding the mandatory share of biofuels in the total motor fuel consumption have been developed in Ukraine; however, they have been repeatedly postponed or cancelled.

The latest attempt was the adoption of amendments to national legislation mandating the use of liquid biofuels (biocomponents) in the transport sector in June 2024 (Verkhovna Rada of Ukraine, 2024). It mandates a minimum of 5% biofuel components from 1 May 2025.

This provision has been postponed, and liability for non-compliance is not to be applied until January 1, 2026. Currently, there is a need to develop integrated scenarios for the production of liquid biofuels in Ukraine to shape a long-term energy strategy, strengthen energy security, support the sustainable development of the biofuels industry, integrate into the European energy space, and achieve climate goals to reduce CO_2 emissions.

The scenarios will provide the share of bioethanol and biodiesel in total motor fuel consumption. They will take into account various options for the pathway development: starting from the pessimistic one, when the key benchmark is only the mandatory share of biocomponents in fuel in the amount of 5% and ending with the optimistic one, where Ukraine moves towards European standards and has a 15-20% share of biofuels in total consumption (Table 3).

Table 3 presents three composite scenarios for the development of biofuel production in Ukraine: a pessimistic scenario (S1), a realistic scenario (S2), and an optimistic scenario (S3). Each scenario included a baseline model for the use of agricultural feedstocks, a planned structure of biofuel production and consumption, key development factors, and the share of renewable energy and biofuels in total transport fuel consumption.

An analysis of the combined scenarios shows that the dynamics of biofuel production and consumption in Ukraine depend primarily on the combined impact of political, economic, and technological factors. The S_1 scenario represents an export-oriented economy with insufficient government support, resulting in a biofuel share of only 5-6% (compared to 12-14% from renewable energy in the transport sector). The S_2 scenario illustrates that economic recovery and moderate technological progress will increase the share of biofuels to 10-12% (with renewable energy accounting for 17-20%). The S_3 scenario indicates that government support, the development of new technologies, and European integration will lead to a biofuel share of 15-20% (with renewable energy accounting for 20-25%). These scenarios reflect varying degrees of influence from factors such as legislation, infrastructure, investment, technological development, and a focus on domestic consumption or exports.

Using the authors' methodology, the percentage shares of bioethanol ($a_{bioeth.}$) and biodiesel ($a_{biodies.}$) in the replacement of conventional fuels under different scenarios in Ukraine were calculated in the ratio of 30:70. The results of the calculations are summarised in Table 4 with the obtained target indicators for each scenario.

Table 3. Integrated Scenarios for Biofuel Production and Consumption (Bioethanol and Biodiesel) in Ukraine up to 2035.

Scenario	Basic Agricultural Use Pattern	Biofuel Production and Consumption Pattern	Key Driving Forces	Share of RES in Transport Sector*	Bioethanol & Biodiesel Share
S_1 (Pessimistic)	Predominantly food use	Bioethanol: partial domestic use and export; export-oriented production. Biodiesel: export-oriented feedstock; limited domestic consumption (mainly cooperatives).	- Prolonged martial law; infrastructure destruction; instability of feedstock supply. -High share of feedstock and bioethanol exports due to favourable foreign prices and high domestic production costs. - Limited state support; mandatory biocomponent requirement remains at 5%. - Weak innovation, logistical constraints, certification barriers, and low investment activity.	12–14%	5–6%
S_2 (Realistic)	Mixed food and energy use, with predominance of food use	Bioethanol: partial domestic use and export; export-oriented. Biodiesel: export-oriented feedstock; increasing domestic production by cooperatives and specialized enterprises.	- End of martial law in 2026–2027; gradual economic recovery; activation of domestic investment. - Continued feedstock exports with moderate expansion of biodiesel production. - Improvement of legislation; increase in mandatory biocomponent share; tax incentives and subsidies. - Moderate technological development (mainly first-generation biofuels).	17–20%	10–12%
S_3 (Optimistic)	Mixed food and energy use, with predominance of energy use	Bioethanol: primarily domestic consumption; partial export. Biodiesel: primarily domestic consumption; partial export.	- End of martial law (2026); transition to green recovery and economic growth; strong logistics and capital inflows. - Significant expansion of bioethanol and biodiesel production capacity. - Alignment with EU biofuel targets; sustainability compliance; comprehensive state support mechanisms. - Development of first- and second-generation biofuel technologies (including non-food feedstock and waste).	20–25%	15–20%

Table 4. Scenario-Based Shares of Bioethanol and Biodiesel in Replacing Conventional Fuels in Ukraine.

Scenario	Total share of biofuels, (a)	Share of bioethanol ($a_{bioeth.}$)	Share of biodiesel ($a_{biodies.}$)
Pessimistic (S_1)	6%	0.06 x 0.3 = 0.018 (1.8%)	0.06 x 0.7 = 0.042 (4.2%)
Realistic (S_2)	12%	0.12 x 0.3 = 0.036 (3.6%)	0.12 x 0.7 = 0.084 (8.4%)
Optimistic (S_3)	20%	0.20 x 0.3 = 0.060 (6.0%)	0.20 x 0.7 = 0.140 (14.0%)

The calculations showed that under the pessimistic scenario, the share of bioethanol replacing conventional fuels will amount to 1.8% and that of biodiesel to 4.2%; under the realistic scenario, 3.6% and 8.4%, respectively; and under the optimistic scenario, 6.0% and 14.0%.The results of calculations of the physical volumes of bioethanol production (Q_{bioeth}) and biodiesel production ($Q_{biodies}$) under the proposed scenarios are presented in Table 5.

Table 5. Scenario-Based Potential Volumes of Bioethanol and Biodiesel in Ukraine (million tons).

Scenario	Volume of bioethanol ($Q_{bioeth.}$)	Volume of biodiesel ($Q_{biodies.}$)	Total volume of biofuels (Q) (bioethanol + biodiesel)
Pessimistic (S_1)	9 x 0.018 = 0.162	9 x 0.042 = 0.378	0.540
Realistic (S_2)	9 x 0.036 = 0.324	9 x 0.084 = 0.756	1.080
Optimistic (S_3)	9 x 0.060 = 0.540	9 x 0.140 = 1.260	1.800

The calculations showed that, based on a total fuel consumption of 9 million tons (average for 2020–2025 in Ukraine) (State Statistics Service of Ukraine, 2025), the volume of bioethanol and biodiesel production and consumption will increase progressively across the scenarios.

Under the pessimistic scenario (S_1), bioethanol and biodiesel are expected to reach 0.162 and 0.378 million tons, respectively, for a total of 0.540 million tons. In the realistic scenario (S_2), bioethanol production and consumption increased to 0.324 million tons, whereas biodiesel reached 0.756 million tons, for a total of 1.080 million tons. Finally, in the optimistic scenario (S_3), bioethanol and biodiesel were projected at 0.540 million and 1.260 million tons, respectively, resulting in a total of 1.800 million tons.

The next stage will involve calculating the area required to grow energy crops to produce biofuel at the volumes specified for each scenario. It was determined that energy use is appropriate for a portion of wheat, corn, and sugar beets (for bioethanol production) and rapeseed (for biodiesel production).

In the calculations, the average crop yield over the previous five years, bioethanol yield per 1 ha, and estimated volumes required for bioethanol and biodiesel production were considered (Table 6). Based on the calculations, it was found that implementing a pessimistic scenario would involve using 1.8% of the average cropping area for 2020-2023, a realistic scenario of 3.5%, and an optimistic scenario of 5.9% (State Statistics Service of Ukraine, 2025).

The selection of optimal crops for bioethanol production is of great importance. In our calculations, we assumed that bioethanol production in Ukraine would be predominantly based on corn and sugar beet (40% each of the total feedstock potential), with wheat accounting for 20% (State Statistics Service of Ukraine, 2025).

It is assumed that rapeseed will serve as the primary crop to ensure the required volume of biodiesel production, given the high demand for sunflower oil and favourable food market prices. In Ukraine, biodiesel production from soybeans is less efficient than that from rapeseed.

Table 6. Area Requirements for Crop Production under Biofuel Scenarios in Ukraine.

Crop (share of total feedstock potential)	Average crop yield in 2020-2024, centners per ha	Biofuel output, t/ha	Required area for growing crops, thousand ha		
			Pessimistic scenario 6%	Realistic scenario 12%	Optimistic scenario 20%
Bioethanol					
Wheat (20%)	43.0	1.24	26.1	52.3	87.1
Corn (40%)	68.2	1.93	33.6	67.2	111.9
Sugar beet (40%)	493.3	3.71	17.5	34.9	58.2
Total	x	x	77.2	154.4	257.2
Biodiesel					
Rapeseed (100%)	27.74	0.99	381.8	763.6	1,272.8
Bioethanol and Biodiesel					
Total	x	x	459.0	918.0	1,530.0
Share of the average cropping area in 2020-2023 (25,735.2 thousand ha), % *	x	x	1.8%	3.6%	5.9%

*Note: *Statistical data for 2024 are unavailable due to the lack of statistical and administrative data sources required for the calculations.*

5. Discussion.

The conducted research showed that, since crops have both food and bioenergy potential, it is important to identify the most effective uses for them. Koval et al. (2025) and Talavyria et al. (2025) emphasise the significant bioenergy potential of crops grown in Ukraine. Unlike existing studies, an algorithm was developed for selecting crops for food/energy use, enabling the selection of an optimal strategy and ensuring maximum benefits.

When studying the current state of bioethanol and biodiesel production, a limitation was that aggregated data by country were available only until 2023. Data for Ukraine is limited due to martial law, so some statistical information is not publicly available. Based on Pryshliak et al. (2022), the prospects for bioethanol and biodiesel production at the national level were outlined, specific scenarios were identified, and the likelihood of their implementation was assessed.

The developed integrated scenarios, especially the realistic and optimistic ones, align with Ukraine's strategic development priorities, which are oriented towards European environmental standards and energy targets (Cabinet of Ministers of Ukraine, 2024).

In particular, they will contribute to the implementation of the European Green Deal (European Union, 2019), and the Paris Agreement (United Nations, 2015). The implementation of the developed scenarios for bioethanol and biodiesel, as well as the integrated scenarios for liquid biofuels, is significantly affected by the socio-economic and security conditions in the country. The prolonged continuation of martial law, missile attacks, and the occupation of part of Ukraine's territory led to the deterioration of the country's investment climate.

Therefore, the probability of investment in bioenergy projects by both domestic and foreign investors under such conditions is reduced. Papagianni et al. (2024) showed that investments are the key driving force behind the development of biofuel production across generations.

The implementation of the developed integrated scenarios for the production and consumption of liquid biofuels in Ukraine, especially the realistic and optimistic scenarios, will contribute to achieving the UN Sustainable Development Goals by 2030 (Goal 7 & 12). This will contribute to the implementation of the European Green Deal and fulfil the country's environmental obligations under international agreements.

Possible inaccuracies in calculating the required cropping area for growing biofuel crops in Ukraine when implementing different scenarios are justified by the fact that the calculations were based on the average cropping area of Ukraine for 2020-2023. Due to martial law and the occupation of part of Ukraine's territory, statistical data on the 2024 cropping area are unavailable.

Unlike Kaletnik & Pryshliak (2021) and Tokarchuk et al. (2022), only four agricultural crops were selected for biofuel production scenarios: wheat, corn, sugar beet, and rapeseed. According to this algorithm, these species possess the highest bioenergy potential.

6. Conclusions.

The study confirms the strategic importance of the biofuels industry as a component of Ukraine's energy security and its integration into the European energy space. The algorithm, developed to choose between food and energy use for agricultural crops, will allow the state to make informed decisions on state support for biofuel production from the most profitable feedstock.

Analysis of the global bioethanol production shows that the USA and Brazil remain the leaders. To realise the potential of bioethanol production in Ukraine, it is advisable to introduce a mandatory bioethanol blend in gasoline, gradually increasing it, and to adopt modern bioproduction technologies. Four scenarios have been developed for the Ukrainian market: from export-oriented feedstock to a combined one (domestic use and exports of finished products). The combined scenario is the most realistic for Ukraine.

It has been established that global biodiesel production volumes are growing annually, indicating strong prospects for this bioenergy sector. However, in Ukraine, the industry has not been developed significantly. It can be explained by the high level of feedstock exports (rapeseed) and the high excise tax on finished products.

The developed scenarios for biodiesel production in Ukraine show those different options are possible, ranging from maintaining the country's role as a feedstock supplier to positioning it as a producer of value-added finished products for both domestic and international bioenergy markets.

Based on the analysis of the current state of liquid biofuel production and the baseline scenarios it was developed for bioethanol and biodiesel in Ukraine, three complex scenarios were developed: pessimistic, realistic, and optimistic. They offer different options for ending martial law, for stimulating the economy, and for developing industry. Each scenario contains target indicators for replacing conventional fuels with biofuels (6%, 12%, and 20%). The developed scenarios serve as the basis for strategic planning for bioenergy development in Ukraine.

The calculation of the required cropping areas for bioenergy crops shows that, under the optimistic scenario, about 5.9% of the average cropping area (2020-2023) is required, while under the pessimistic scenario, only 1.8% is required. The most significant contribution to bioethanol production will come from corn and sugar beets, while rapeseed will mainly contribute to biodiesel production. In this way, Ukraine's energy security can be improved without threatening food security.

The results of the study can serve as a scientific and analytical basis for shaping Ukraine's state policy in the field of bioenergy, developing a strategy for domestic biofuel production, improving the regulatory framework, and attracting investment into the sector.

Conflict of Interest Statement.

The authors declare that there is no conflict of interest.

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