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PROSPECTS AND PROBLEMS OF BIODIESEL FUEL PRODUCTION

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The article examines the physicochemical properties of fuels for internal combustion engines, focusing on key aspects such as elemental composition, heat of combustion, density, viscosity, etc. The prerequisites and stages of developing alternative fuels, particularly for compression ignition engines, are analyzed, with biodiesel fuel taking a prominent place. Chemically, biodiesel consists of methyl esters of fatty acids (lipids) and, due to its physicochemical properties, closely resembles conventional diesel fuel, allowing for mixing in various proportions. The paper discusses the most well-known biodiesel production methods, including transesterification (conventional, supercritical, enzymatic), pyrolysis, and hydrogenation (second-generation biodiesel), providing an overview of the mechanisms involved. The classical transesterification process is identified as the most promising for Ukraine. The study outlines the methods of classical transesterification and presents a schematic of the process. The article also describes the nomenclature of equipment for biodiesel production. It provides technical characteristics of some devices, including the BDD-200 biodiesel production line used in the alternative energy laboratory of Vinnytsia National Agrarian University. Scientific research on biodiesel production in Ukraine and key authors in this field are reviewed. Special attention is given to raw material resources for biodiesel fuel production. The study elaborates on classical transesterification technologies, including intermolecular and intramolecular transesterification, and alcoholysis, presenting fundamental chemical reactions involving methanol or ethanol. The advantages and disadvantages of various catalysts, such as potassium hydroxide and sodium hydroxide, are also discussed. This scientific paper presents the results of the initiative research project 0122U002187.

Key words: *physicochemical indicators, fuel, biodiesel fuel, transesterification, methods, processes, chemical reaction, technological process.*

Eq. 5. Fig. 2. Table. 1. Ref. 29.

1. Problem formulation

Current trends in the energy sector indicate the need to transition to sustainable and environmentally friendly energy sources. The main volume of fuel used today is petroleum products, in particular diesel fuel, which is widely used in transport, agriculture and industry. However, its use is accompanied by significant emissions of greenhouse gases and harmful substances that contribute to the deterioration of the environmental situation and accelerate the processes of climate change. In addition, there is a steady trend towards the depletion of natural fossil resources, which makes the issue of finding alternative types of fuel extremely relevant.

Biodiesel fuel, produced from renewable raw materials – vegetable oils, animal fats and used edible fats, is considered one of the most promising alternative energy sources. Due to its physicochemical properties, biodiesel is close to traditional diesel fuel in a number of parameters, which makes it possible to use it without significant changes in the design of engines.

Nevertheless, despite the environmental and technological advantages, the large-scale introduction of biodiesel in the fuel and energy complex faces a number of significant problems. These include high production costs, the need to modify engines, limited raw material base, potential competition with the food sector for agricultural land, and insufficient regulatory support from the state.

Thus, the problem of the study is the need for a comprehensive analysis of modern biodiesel production technologies, an assessment of its efficiency and environmental safety, as well as the development of practical recommendations for optimizing production processes and introducing biofuels into the country's energy policy.

2. Analysis of recent research and publications

The modern world faces an acute problem of depleting natural resources and increasing environmental burdens due to the use of fossil fuels. Petroleum products, particularly diesel fuel, are key energy sources for transportation, industry, and agriculture; however, their use leads to significant greenhouse gas emissions, harmful substances, and environmental pollution.

Biodiesel production and usage are considered promising alternatives to traditional diesel fuel, reducing dependence on imported energy resources and improving environmental conditions. Biodiesel is derived from renewable sources such as vegetable oils, animal fats, and used cooking oils, making it a sustainable energy resource.

Despite its significant potential, the large-scale adoption of biodiesel faces several challenges:

- economic barriers: High production costs compared to traditional diesel, especially in volatile oil markets.
- technical limitations: The need to modify diesel engines and fuel systems for efficient biodiesel use.
- environmental risks: Large agricultural land requirements for raw material cultivation may compete with food production.
- regulatory issues: Lack of clear government policies to support biodiesel production and the biofuel industry.

Given these factors, the relevance of this study lies in the comprehensive analysis of biodiesel production technologies, assessment of its advantages and disadvantages, and development of recommendations for optimizing production and integrating biodiesel into the fuel and energy sector.

Research objectives:

- analysis of the current state of biodiesel production worldwide and in Ukraine.
- study of the physicochemical properties of biodiesel and its impact on diesel engine performance.
- examination of existing biodiesel production technologies and their efficiency.
- identification of key economic and environmental barriers to large-scale biodiesel adoption.
- development of recommendations for improving production technologies and state policies in the biofuel energy sector.

3. The purpose of the article

The main goal of the study is to contribute to the development of the biodiesel industry, ensuring energy independence and reducing the negative environmental impact of agricultural machinery.

To achieve this goal, the following objectives have been set:

- analysis of the global and Ukrainian biodiesel production landscape.
- investigation of biodiesel's physicochemical properties and its effects on diesel engine operation.
- examination of existing biodiesel production technologies and their efficiency.

4. Results and discussion

When producing alternative fuels, it is essential to consider their quality indicators, particularly the physicochemical properties of liquid fuels for diesel engines, which characterize traditional petroleum-based fuels. These include the fuel's chemical elemental composition, the heat of combustion, stoichiometric parameters, density, and viscosity (including dynamic, kinematic, and conditional viscosity). Other key factors include the presence of mechanical impurities and water in the fuel, fuel stability (both physical and chemical), the presence of resinous substances (both actual and potential resins), corrosion properties, the presence of water-soluble acids and alkalis, organic acids, and sulfur compounds in fuels.

The elemental composition of the fuel is a crucial hematological indicator, determined by the formula [1]:

$$C^p + H^p + O^p + N^p + S^p + A^p + W^p = 100\%, \tag{1}$$

where $C^p, H^p, O^p, N^p, S^p, A^p, W^p$ – ash, and moisture represent the working masses of the fuel components in percentage terms: carbon, hydrogen, oxygen, nitrogen, sulfur, ash, and moisture.

Knowing the quantity of the first three components in equation (1), the lower heating value of the fuel (kJ/kg) can be calculated using D.I. Mendeleev's equation [2]:

$$\mathrm{Q_н} = 339 \cdot \mathrm{C} + 1256 \cdot \mathrm{H} - 109 \cdot \mathrm{O} - \frac{25{,}14 \cdot 9 \cdot \mathrm{H}}{100}, \tag{2}$$

where C, H, S, O – are the respective chemical elements of the combustible part of the fuel, expressed as a percentage by mass.

The stoichiometric parameters of the fuel are crucial characteristics that determine the completeness of fuel combustion. They are primarily characterized by the excess air ratio, which is calculated using the following formula [1], kg/kg:

$$\lambda = \frac{L_a}{L_t} \tag{3}$$

where L_a and L_t are the actual amount of air entering the engine cylinder and the theoretically required amount of air for the combustion of one kilogram of fuel, respectively.

The theoretically required amount of air is calculated using the following formula, kg:

$$L_t = \frac{2{,}67 \cdot C + 8 \cdot H + S - O}{30}. \tag{4}$$

As we can see, stoichiometric parameters also depend on the elemental composition of the fuel.

The following can be considered alternative fuels for compression ignition engines:

- the use of vegetable oil in diesel engines;
- operation of diesel engines on a mixture of vegetable oil and diesel fuel;
- biodiesel fuel;
- synthetic diesel fuel (GTL – Gas-to-Liquids);
- hydrogen;
- biomethane;
- water-diesel emulsions.

The use of vegetable oil was first proposed by Rudolf Diesel, and his initial engine prototypes operated on vegetable oil. However, modern engines face significant challenges when running on oil due to its different physicochemical properties compared to diesel fuel [3].

Therefore, when using vegetable oil in diesel engines, it is recommended to mix it with standard diesel fuel. Straight Vegetable Oil (SVO) blends are typically prepared with a specific percentage of oil and diesel fuel. The most common blend consists of 20% vegetable oil and 80% diesel fuel. However, SVO-diesel mixtures tend to separate over time.

Biodiesel fuel, obtained through the transesterification of vegetable or animal fats, is the closest to standard diesel fuel in terms of its physicochemical properties.

Synthetic diesel fuel (GTL – Gas-to-Liquids) is produced from natural gas or biomass using the Fischer-Tropsch process. However, this technology is complex and expensive.

To use hydrogen in diesel engines, certain modifications are required. Hydrogen has a high heat of combustion and does not produce CO_2 during combustion. However, the main drawback of hydrogen as a fuel is its storage difficulty, making it hard to accumulate and requiring on-demand production and consumption.

Biomethane is a renewable gaseous fuel obtained through the anaerobic digestion of agricultural or food industry waste. It can be stored in compressed (CNG) or liquefied (LNG) form. Biomethane can only be used in diesel engines in dual-fuel mode (gas-diesel cycle), which requires modifications to the engine's fuel system. A key disadvantage of biomethane production is that a non-combustible byproduct (CO_2) is produced during the fermentation process, sometimes reaching up to 50% concentration, requiring purification before use.

Water-diesel emulsions are another type of alternative fuel. Adding water to diesel fuel in the form of an emulsion can reduce harmful emissions and improve combustion efficiency. Water-diesel emulsions are created by mixing diesel fuel with water and an emulsifier, which stabilizes the mixture. This process can be performed in real time before injection. The main disadvantage of emulsions is the need for additional equipment to produce the emulsion continuously.

Thus, biodiesel fuel is considered the most promising alternative fuel.

Biodiesel fuel can be produced using various methods, with the main ones being: transesterification of fats, including classical, supercritical, enzymatic, microwave-assisted, and cavitation-assisted methods; pyrolysis; hydrotreatment.

Classical Transesterification. The most common method of biodiesel production is classical transesterification, which involves a chemical reaction between vegetable oil and alcohol. This process replaces glycerine in triglycerides with alcohol molecules, forming fatty acid esters (biodiesel fuel) and a by-product – glycerine, which later precipitates. Methanol or ethanol is used as the alcohol, while potassium hydroxide (KOH) or sodium hydroxide (NaOH) serves as the catalyst. Technological parameters**:** the mixture of reactants is heated to 60-70°C and stirred for 1-2 hours**.**

Supercritical Transesterification. This method is chemically identical to classical transesterification but differs in technological parameters. The alcohol used in the reaction is brought to a supercritical state, where it fills the entire volume like a gas but retains liquid properties, making it an excellent solvent and accelerating the transesterification process**.** For methanol, this supercritical state is reached at a temperature of about 240°C and a pressure of about 8 MPa. Main disadvantage: Requires complex equipment and high energy consumption.

Enzymatic Transesterification – an Innovative Biodiesel Production Method. Enzymatic transesterification is an innovative method of biodiesel production that utilizes enzymes, primarily lipases, instead of traditional chemical catalysts. This process is gaining popularity due to its environmental friendliness, energy efficiency, and the ability to use a variety of raw materials. Lipases are added to the raw material along with alcohol. They can be dissolved in liquid or immobilized on a solid substrate (such as special resins or gels), allowing for multiple uses. The technological parameters of this process differ from classical transesterification. The reaction is carried out at a relatively moderate temperature (30–60°C) in a neutral or slightly acidic environment. Lipases catalyze the breakdown of triglycerides, replacing glycerol with ethyl or methyl esters. The main disadvantage of this process is its longer duration, which can significantly slow down production, especially on a large scale.

Pyrolysis – a Distinct Technology. Pyrolysis is fundamentally different from transesterification and involves the thermal decomposition of organic raw materials (such as vegetable oil) at high temperatures without oxygen, resulting in a biofuel product that serves as a primary component of biodiesel fuel. The technological features include heating the raw material to temperatures between 400°C and 800°C in a specialized reactor while eliminating oxygen. The main drawback of this process is its complexity and the need for further processing.

Hydrotreatment – advanced Fuel Production. Hydrotreatment allows for the production of not only biodiesel but also green crude oil, aviation fuel, and other types of fuel. Biodiesel fuel obtained through hydrotreatment (hydration) in the presence of hydrogen is classified as second-generation biodiesel, which boasts high-quality indicators and meets stricter environmental standards.

Microwave and Cavitation Technologies. These are transesterification processes that use microwave or cavitation treatment to enhance reaction intensity.

Each of these technologies has its advantages and disadvantages and can be chosen based on the type of raw material, production scale, economic conditions, and environmental requirements. In Ukraine, transesterification and pyrolysis appear to be the most promising, as they allow for the use of readily available raw materials and have already been applied to some extent.

Nevertheless, the most widespread method of biofuel production remains classical transesterification. Its chemical-technological aspects are not yet fully explored and can be the subject of scientific research.

Equipment for Biodiesel Production. The equipment available on the market for biodiesel production is listed in Table 1.

Table 1

Comparative Characteristics of Biodiesel Equipment

Indicators	Requirements of SOU 24.14-37-561:2007	Requirements of EN 14214:2003	MZDP-1 LLC "Eleron"	W-400 Porcelak-Invest	LVBD-ECO-BIO-NULESU	Karpaty-50 JSC "Emal-Karpaty"	UEO-200 JSC "Agromash"
Productivity, l/h	-	-	100	400	220	50	200
Installed Power, kW	-	-	44,09	29	55	25	64,8
Characteristics of Biodiesel Fuel:							
- Flash Point, °C	not less than 120	not less than 120	175	160	175	155	153

- Kinematic Viscosity, mm^2/s	3,5-5,0	3,5-5,0	5,0	7,4	4,35	4,64	6,68
- Density, kg/m^3	860-900	860-900	883	883	884	882	897
- Mass Fraction of Water, mg/kg	not more than 500	not more than 500	absent	0,005	absent	absent	absent
- Mass Fraction of Sulfur, mg/kg, not more than	10	10	absent	0,001	0,02	absent	absent
- Content of Mechanical Impurities, mg/kg, not more than	absent	24	absent	absent	absent	absent	absent
- Number of Personnel for Maintenance, persons	-	-	2	1	1	1	1
- Specific Energy Consumption, kWh/l	-	-	0,24	0,055	0,024	0,13	0,20
- Labor Costs, man-hours	-	-	0,025	0,016	0,008	0,002	0,005
Raw Materials	-	-	Oilseed Crops	Oilseed Crops	Oilseed Crops	Oilseed Crops	Vegetable Oils
Purification System	-	-	Oil purification using frame fabric filters. Four-stage biodiesel fuel purification.	Oil purification using frame fabric filters. Biodiesel fuel purification by settling in a tank.	Oil purification using frame fabric filters. Biodiesel fuel purification using a special self-cleaning filter.	Biodiesel fuel purification using a filter.	Biodiesel fuel purification using a filter and settling in a tank

The MZDP-1 mini-plant for biodiesel production, offered by LLC "Eleron," has a capacity of 100 l/h. The technological line is shown in Figure 1. This technological scheme includes the processing of oilseed crops into biodiesel. The set includes an oil press (7) and a filter press (6) for oil purification. In addition to the reactor (1), where the primary transesterification process takes place, and the methanol mixing tank (2) with KOH, the equipment also includes a rectification column (3) and an adsorber (4) to remove methanol from the obtained biodiesel, as well as water tanks (12) and a water heater (11) for water used in purifying biodiesel from by-products (soap). The separation of methyl esters and glycerin occurs in a special separator (13).

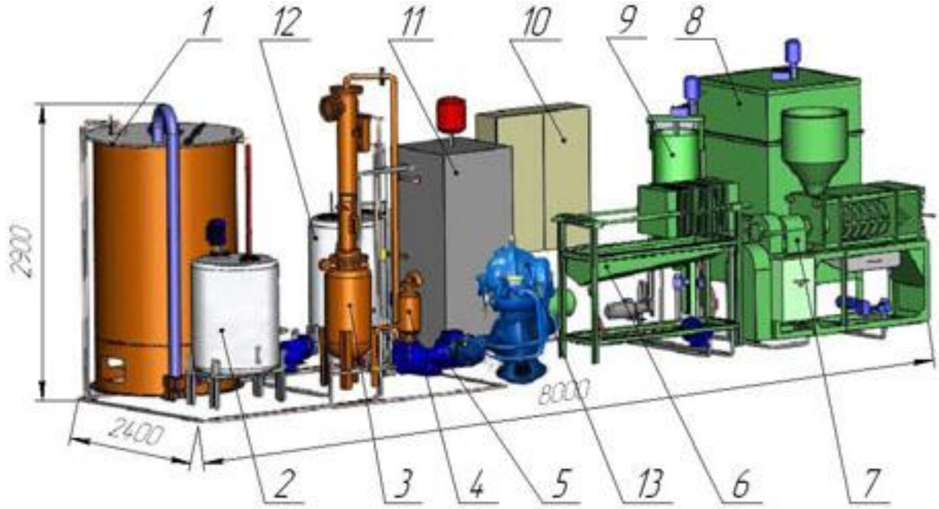

Fig. 1. General Diagram of Equipment for the MZDP-1 Mini-Plant for Biodiesel Production [5]:
1 – reactor; 2 – tank for methanol and KOH mixture; 3 – rectification apparatus; 4 – adsorber; 5 – vacuum pump; 6 – filter press; 7 – oil press; 8 – oil storage tank; 9 – settling tank; 10 – control cabinet; 11 – water heater; 12 – water tank; 13 – separator.

The BDD-200 biodiesel unit, manufactured by a Dnipro-based company, is shown in Figure 2. It has a capacity of 200 l/h. This type of production line is installed in the Alternative Energy Laboratory of Vinnytsia National Agrarian University. A key feature of this line is the ability to operate two reactors (1) simultaneously (in parallel) and two settling tanks, which increases productivity or allows for two parallel transesterifications and settling processes with different parameters at the same time. Additionally, the unit has a methanol counter (4), simplifying reagent dosing for the reaction. This type of production line is suitable for small farms with up to 1000 hectares of arable land.

Ukraine's Potential for Scientific Support in Biodiesel Production. The issue of manufacturing and using alternative fuels has been highlighted in the works of Semenov V.G. [6, 7, 8]. The operation of machine-tractor units (MTUs) on alternative fuels, including biodiesel-diesel fuel blends, and their impact on the technical and economic performance of MTUs, has been examined in the studies [9, 10, 11, 12].

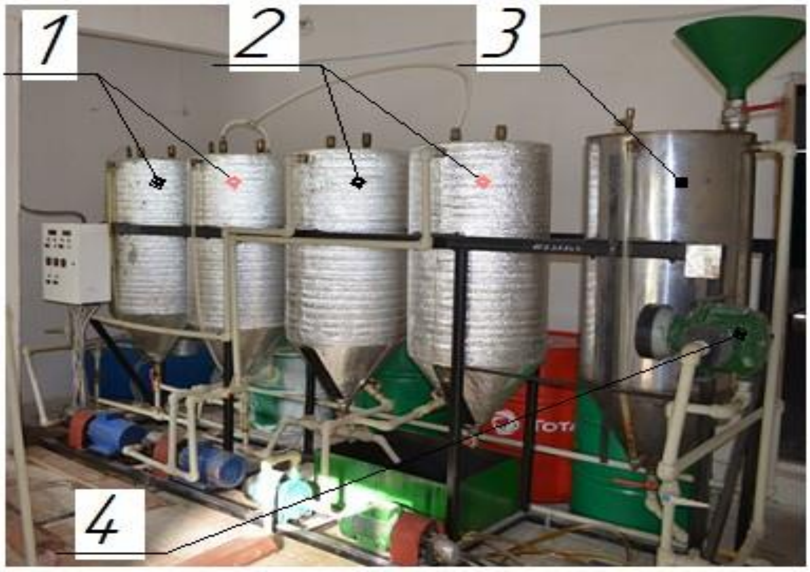

Fig. 2 – Biodiesel Production Line BDD-200:
1 – reactor-mixers; 2 – settling tanks; 3 – methanol tank for mixing KOH with methyl alcohol; 4 – methyl alcohol meter.

The prospects for alternative fuel production, the development of biodiesel manufacturing technologies, and their application have been explored by researchers from the National University of Life and Environmental Sciences, including Dubrovin V.O., Holub H.A., and Chuba V.V. [13, 14, 15].

Scientists from Lviv Polytechnic National University, including Chaikovskyi T.V., Nikitishyn Ye.Yu., Ivasiv V.V., and Sarabun O.Ya., have studied the application of catalysts in the esterification process of vegetable oil [16]. The purification of oil as a raw material for biofuel production has been investigated by Professor Topilin H.Ye. [17, 18].

The use of biodiesel fuels in automotive transport has been examined in scientific works [8, 19, 20, 21, 22, 23].

One of the first people to raise awareness about alternative energy in Ukraine was [24], President of VNAU, Doctor of Economic Sciences, Professor, and Academician of the NAASU. Kaletnik H.M. conducted extensive scientific research on biodiesel fuel production and usage, particularly in his works [13, 26, 27, 28].

A review of the mentioned literature sources and other works dedicated to biodiesel fuel, as well as an analysis of the technical characteristics of equipment for its production, provides a basis to assert that Ukraine has established the scientific and technical prerequisites for the development of biodiesel production, as noted in article [29].

For biodiesel production in Ukraine, it is most rational to use rapeseed, sunflower, and soybean seeds, given the country's vast potential for these crops. With the appropriate cultivation technology, rapeseed yields per hectare include 20 tons of green fodder, 20 tons of green fertilizers, 3–3.5 tons of seeds, 13 centners of oil, 16 centners of oilcake (press residue), 100 kg of honey, and 500 kg of paper.

The most commonly used reaction for biodiesel fuel production is alcoholysis. Methyl alcohol (CH_3OH), the simplest monohydric alcohol, is most frequently used for transesterification. The general equation for transesterification is presented below [30]:

$$\begin{array}{lll} CH_2OC = OR_1 & & CH_3COO - R_2 \\ | & & \\ CHOC = OR_2 + 3CH_3OH \rightarrow (CH_2OH)_2CH - OH + CH_3COO - R_2 & & \\ | & & \\ CH_2COOR_3 & & CH_3CO = O - R_3 \end{array} \tag{5}$$

where R_1, R_2, R_3 – are long chains of carbon and hydrogen atoms.

Additionally, transesterification reactions can also occur with ethyl alcohol (C_2H_5OH). Potassium hydroxide (KOH) and sodium hydroxide (NaOH) can be used as catalysts.

5. Conclusion

The main physicochemical properties of fuels affecting the operation of compression ignition engines were reviewed. It was established that one of the key parameters is the elemental chemical composition of the fuel and its heat of combustion.

The primary types of alternative fuels used in diesel engines were presented. It was determined that biodiesel fuel is the closest to standard diesel fuel in terms of physicochemical properties and mixes well with it.

The main methods and techniques for biodiesel production were analyzed. It was determined that the most straightforward and accessible technology is the classical transesterification process, which can be implemented in agricultural enterprises.

Available biodiesel production equipment on the Ukrainian market was reviewed. It was found that the most well-known and suitable for agricultural producers are the MZDP-1 mini-plant and the BDD-200 production line.

A review of literature sources was conducted, examining the scientific, technical, and technological aspects of biodiesel production and use. Based on the analysis, it was concluded that Ukraine has the scientific and technical potential to establish biodiesel production.

The chemical equation for methanolysis was presented as the most well-known description of the classical transesterification process of vegetable oils.

Although various transesterification reactions involving different alcohols and catalysts have been described in the literature, there are no clear recommendations on which process and under what conditions are optimal for biodiesel production as a substitute for diesel fuel. Further research in this area is required.

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ПЕРСПЕКТИВИ І ПРОБЛЕМИ ВИРОБНИЦТВА БІОДИЗЕЛЬНОГО ПАЛИВА

В статті розглянуті фізико-хімічні властивості палив для двигунів внутрішнього згорання, серед основних, які заслуговують уваги є елементний склад палива, теплота його згорання, густина, в'язкість та ін. Розглянуті передумови та етапи розвитку альтернативних палив, зокрема для двигунів із запалюванням від стиску, серед яких посідає чільне місце так зване біодизельне паливо, що з хімічної точки зору є метиловими ефірами жирних кислот (ліпідів) і за своїми фізико-хімічними властивостями найбільше наближене до стандартного дизельного палива і гарно змішується з ним у різних пропорціях. Розглянуті найбільш відомі способи виробництва біодизельного палива, таких як трансетерифікація, зокрема суперкритична, ензимна, шляхом піролізу, шляхом гідратації (так зване біодизельне паливо другого покоління), та ін. і коротко розглянуті механізми кожного з них. Визначено процес класичної трансетерифікації як найбільш перспективний в Україні. Визначено методи проведення класичної трансетерифікації, наведено принципову схему цього процесу. Розглянута номенклатура обладнання для виробництва біопалива та його короткі технічні характеристики. Наведена лінія з виробництва біопалива БДД-200, що використовується в лабораторії альтернативної енергетики ВНАУ. Розглянуті наукові роботи присвячені виробництву біопалива в Україні та їх авторів. Приділено увагу сировинним ресурсам для виробництва біодизельного палива. Детально розглянуті технології класичної переетерифікації, зокрема міжмолекулярна переетерифікація, внутрішньомолекулярна переетерифікація, алкоголіз та ацидоліз, представлено базові хімічні реакції, що відбуваються в процесі переетерифікації, зокрема з використанням метанолу або етанолу у якості спирту. Розглянуті переваги й недоліки використання різних каталізаторів – гідрооксиду калію та гідрооксиду натрію. В даній науковій праці представлені результати виконання ініціативної науково-дослідної роботи 0122U002187.

Ключові слова: *фізико-хімічні показники, паливо, біодизельне паливо, трансетерифікація, методи, способи, хімічна реакція, технологічний процес.*

Ф. 5. Рис. 2. Табл. 1. Літ. 29.

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