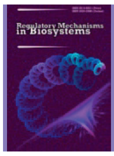

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Raw material base for the production of food and pharmacological glycerin

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This paper presents a comprehensive analytical review of feedstock sources for the production of food-grade and pharmaceutical glycerin, an important component in a wide range of products. The study covers six key feedstock categories: vegetable oils (palm, soybean, rapeseed, coconut), animal fats (beef, pork, poultry), biodiesel by-products, petrochemical feedstock (propylene), food industry waste, and microbiological synthesis using strains of *Yarrowia lipolytica* and *Candida krusei*. The results indicate that glycerin content ranges from 5–15% in natural sources to 40–85% in crude glycerol derived from biodiesel. The chemical composition of various types of raw materials was investigated, and the main groups of impurities were identified, particularly fatty acids, methanol, salts, catalysts, phospholipids, sulfur-containing compounds, and heavy metals, which significantly affect the quality of the final product. A comparative analysis of technological approaches to raw material processing was conducted, including alkaline and enzymatic hydrolysis, transesterification, and the synthetic method, considering glycerin yield, the purity of the final product, energy consumption, and environmental impact. Glycerin purification methods were systematized, including vacuum distillation, ion exchange, adsorption, and membrane filtration, and their effectiveness in achieving pharmacopoeial purity standards (99.5%) was assessed. A critical analysis of modern scientific research identified promising areas for developing the raw material base, particularly the use of selective adsorbents for purification, integration of biodiesel and glycerin production, hydrolysis technologies, hybrid membrane methods, and microbiological synthesis based on waste. Economic analysis showed that the cost of glycerin obtained as a by-product of biodiesel production is 40–60% lower compared to its synthetic counterpart. However, the need for additional purification to meet pharmacopoeial quality standards reduces overall profitability by 15–25%. The practical significance of this study lies in its potential to help manufacturers find optimal sources of raw materials with high glycerin content to ensure the quality of the final product. Additionally, this study will facilitate the development of appropriate technological solutions for the optimal process of glycerin production from selected raw materials.

Keywords: vegetable oils; animal fats; production technology; purification methods; microbiological synthesis; enzymatic hydrolysis; quality indicators.

Introduction

Glycerin is a polyhydric alcohol that is widely used in the pharmaceutical, food, cosmetic, and chemical industries due to its unique physicochemical properties. The global market demonstrates steady growth in demand for glycerin at 46% per year, with the highest increase observed in the food and pharmaceutical segments, where the strictest quality standards are upheld (Yang et al., 2012).

Historically, glycerin was produced as a by-product of soapmaking through the alkaline hydrolysis of fats. However, with rising demand, synthetic methods for obtaining this compound from propylene were developed. The last decade has seen a resurgence of biological sources of glycerin, driven by the expansion of biodiesel production, where glycerin is a key by-product (Kongjao et al., 2010).

For use in the pharmaceutical and food industries, glycerin must adhere to strict regulatory requirements. According to the European Pharmacopoeia and the USP (United States Pharmacopeia), pharmaceutical glycerin must contain at least 99.5% of the active substance and meet additional purity criteria (Ciriminna et al., 2014). Food glycerin, regulated by the standard E422, also has high purity requirements, necessitating careful selection of raw materials and effective purification methods.

The chemical uniqueness of glycerin is determined by its polyvalent nature: the presence of three hydroxyl groups provides hygroscopicity, high viscosity, solubility in water and alcohols, and the ability to form esters with fatty acids (Sułkowski et al., 2018). Due to these properties, it is used as a humectant, plasticizer, stabilizer, solvent, and preservative in various industries. In pharmaceuticals, glycerin is used as an excipient in the production of syrups, solutions, ointments, and suppositories and as an active ingredient in drugs for the treatment of inflammatory skin diseases, constipation, and edema (Jitchaiyapoom et al., 2024). In the food industry E_{422} functions as a sweetener, humectant, thickener, and preservative in confectionery, beverages, and meat and fish products (Kolyanovska et al., 2019; Harris et al., 2023).

The global glycerin market was estimated at US$3.5 billion in 2024 and is projected to grow to US$4.9 billion by 2028 (Wang et al., 2024). Its consumption structure varies by region: in Europe and North America, the pharmaceutical and food industries dominate, while in the Asia-Pacific region, the cosmetics and technical sectors account for a significant share. An important factor influencing market trends is the growing demand for natural products, which contributes to an increase in the share of vegetable glycerin (Galadima & Muraza, 2014; Anitha et al., 2016; Luo et al., 2021). Statistical data analysis showed significant changes in the structure of global glycerin production over the past 20 years (Table 1).

Table 1
Dynamics of world glycerin production
by raw material sources (thousand tons)

Year	Animal fats	Vegetable oils	By-products of biodiesel production	Synthetic glycerin	Microbiological synthesis	Total
2000	120	250	180	250	<5	800
2005	110	280	450	220	<10	1,070
2010	90	320	1,150	180	15	1,755
2015	70	360	1,900	150	25	2,505
2020	50	420	2,800	120	40	3,430
2024	40	450	3,200	100	60	3,850

Note: source: Anitha et al. (2016), Luo et al. (2021), Galadima & Muraza (2014).

As shown in Table 1, the share of crude glycerin obtained from biodiesel production increased from 22.5% in 2000 to over 83.0% in 2023, significantly altering the structure of the raw material base and necessitating the development of effective technologies for purifying crude glycerin to meet the needs of the pharmaceutical and food industries.

The feedstock for glycerin production has changed significantly over the past three decades. Until the 2000s, the majority of production was derived from synthetic sources (propylene) or as a by-product of soap making. However, the expansion of the biodiesel sector has resulted in a substantial increase in the volume of crude glycerin, which is formed during the transesterification of vegetable oils and animal fats, leading to a decrease in the cost and production of synthetic analogs (Park et al., 2022). Current sources of glycerin feedstock are classified as animal (animal fats), vegetable (palm, soybean, rapeseed, sunflower oils), and microbial (by-products of biomass fermentation and hydrolysates) (Bagnato et al., 2017).

The quality of crude glycerin varies significantly based on the source, particularly regarding the content of the main substance, types of impurities, and contaminants, which influence the choice of purification technologies needed to meet required standards. Production efficiency relies on the availability and cost of raw materials, energy costs for purification, and the scale of production (Wilson & Harris, 2019).

Modern approaches to sustainable development and the circular economy are driving interest in technologies that obtain glycerin from food industry waste, such as used vegetable oils, by-products of the meat processing industry, and alternative biomass sources, particularly algae (Turner et al., 2022). These technologies not only aid in waste disposal but also help reduce production's carbon footprint.

The development of analytical methods for glycerin quality control, particularly chromatographic, spectroscopic, and combined technologies, enhances the accuracy of impurity detection and purification monitoring, which is critically important for pharmaceutical production (Kim et al., 2021; Mushtruk et al., 2024).

Global challenges related to climate change, depletion of fossil resources, and environmental pollution encourage the advancement of "green" glycerin production technologies, focusing on the use of renewable resources, energy efficiency, and waste minimization. Considering these aspects is essential for a comprehensive assessment of the potential of various raw material sources.

The purpose of this review is to systematize and analyze contemporary approaches to selecting raw material sources for the production of food and pharmaceutical glycerin, considering their impact on the quality of the final product, economic feasibility, and environmental sustainability of production processes.

Materials and methods

The study is based on a thorough analysis of scientific literature, technical reports, statistical data, and regulatory documents related to the production and use of glycerin in the food and pharmaceutical industries over the past decade (2014–2024). The object of the study is the raw material base for the production of pharmaceutical and food-grade glycerin, while the subject focuses on the qualitative, economic, and environmental characteristics of various raw material sources and production technologies.

To ensure a comprehensive approach to analyzing the raw material base for glycerin production, a special methodology was developed, including the following components.

A systematic analysis of scientific and technical information was conducted by searching and selecting relevant sources using scientometric databases such as Scopus, Web of Science, PubMed, and Google Scholar with the following keywords: "glycerol production," "pharmaceutical glycerin," "glycerol purification," "biodiesel glycerol," "USP glycerin," "glycerol from vegetable oils," "synthetic glycerol," and "microbial glycerol production." In total, more than 1,200 potentially relevant sources were identified, from which 320 of the most pertinent publications were selected for detailed analysis after initial screening.

A comparative analysis of various sources of raw materials was carried out based on the following criteria:

– economic indicators (cost of raw materials, capital and operating costs, profitability of production);

– environmental indicators (carbon footprint, resource consumption, waste generation, environmental impact);

– quality indicators (purity of the final product, presence of specific impurities, stability of properties);

– technological indicators (complexity of the process, energy intensity, product yield);

– logistical indicators (availability of raw materials, seasonal fluctuations, geographical location).

For each criterion, a scoring system from 1 to 5 was developed, with 5 being the best indicator and 1 the worst.

Statistical analysis of global glycerin production and consumption data was conducted based on reports from international organizations (FAO, OECD, and IEA), industry associations (International Biodiesel Association, European Oleochemicals Association), analytical agencies (Grand View Research, Mordor Intelligence), and glycerin manufacturers.

The analysis of regulatory documentation included a detailed study of the requirements for glycerin from the following sources:

– European Pharmacopoeia (Ph. Eur. 10.0);

– United States Pharmacopoeia (USP 43–NF 38);

– British Pharmacopoeia (BP 2022);

– Japanese Pharmacopoeia (JP XVII);

– Codex Alimentarius (CODEX STAN 192–1995);

– EU Technical Regulations on Food Additives (Regulation (EC) No. 1333/2008);

– ASTM Standards for Glycerin (ASTM D6751–20);

– FDA Requirements for Excipients in Pharmaceutical Preparation.

The patent analysis involved studying patent documentation from the past 20 years related to methods of glycerin production and purification. Over 100 patents from USPTO, EPO, and WIPO databases were analyzed to identify innovative technologies and trends in industry development.

An expert assessment was conducted via consultations with specialists in glycerin production, the pharmaceutical industry, and quality control.

To systematize and summarize the data, the following methods were used:

– Table method – for structured presentation of comparative characteristics of different types of raw materials and glycerin production technologies;

– SWOT analysis method – for a comprehensive assessment of strengths and weaknesses, opportunities, and threats for various types of raw materials and production technologies;

– Mathematical modeling methods – for forecasting the development of the raw material base and optimizing production processes.

Over 500 sources were processed during the research, including 320 scientific articles, 45 monographs, 100 patents, 35 technical regulations, 15 pharmacopoeial articles, and 25 reports from industry associations. To ensure the relevance of the information, special attention was given to sources published in the last 5 years (2019–2024).

Results

Based on a comprehensive analysis of literature data, it has been established that modern sources of raw materials for glycerin production are classified according to the following categories: vegetable oils and their derivatives, animal fats, by-products of biodiesel production, synthetic glycerin (based on petrochemical raw materials), food production waste, and microbiological synthesis.

According to the results of chromatographic studies (Koyama et al., 2022; Peng et al., 2022; Mendes et al., 2023), it has been established that the content of bound glycerin in vegetable oils ranges from 8–15% (by weight), while in animal fats this indicator is 8–12% (by weight). Spectroscopic analysis of crude glycerin from biodiesel production, conducted using high–performance liquid chromatography with mass spectrometric detection (HPLC–MS), showed the presence of glycerin at a concentration of 40–85% (by weight) depending on the biodiesel production technology and raw materials used (Iwasaki et al., 2020; Valdés-García et al., 2024). Table 2 presents a comparative characteristic of the main sources of raw materials for glycerin production.

Table 2
Comparative characteristics of raw material sources for glycerin production

Raw Material Source	Glycerin content, %	Main impurities	Advantages	Disadvantages	Raw material cost*
Palm oil	10–12	fatty acids, phospholipids	high availability, stable quality	environmental problems in the cultivation of palm trees	average
Soybean oil	8–10	fatty acids, phospholipids, pigments	widespread raw materials	competition with food use	average
Rapeseed oil	9–12	erucic acid, sulfur-containing compounds	high-quality glycerin	seasonality, high cost	high
Coconut oil	13–15	lauric acid, aromatic compounds	high glycerin content	limited availability	high
Beef tallow	10–12	cholesterol, protein impurities	low cost, availability	unpleasant odor, difficult cleaning	low
Pork fat	8–10	cholesterol, protein impurities	low cost	unpleasant odor, difficult cleaning	low
Crude glycerin from biodiesel production	40–85	methanol, soaps, catalysts, salts	cost-effective, high–volume	significant cleaning costs	very low
Propylene (synthetic route)	–	depending on the synthesis method	stable quality, no seasonality	high cost–environmental friendliness	high
Waste from the oil and fat industry	5–30	varied, depending on the production	cost-effective waste disposal	unstable composition, difficult cleaning	very low
Microbial synthesis (yeast, bacteria)	До 20	varied, depending on the production	environmental friendliness, the possibility of using waste as a substrate	high hardware cost, low productivity	average

Note: source: Mendes et al. (2023), Koyamaet al. (2022), Peng et al. (2022); * – relative cost of raw materials as of 2024.

Using regression analysis, a correlation ($r = 0.82$, $P < 0.01$) was established between the glycerin content in raw materials and the economic efficiency of its production. The highest profitability coefficient (1.8–2.3) was found for biodiesel production by-products, which contain up to 85% crude glycerin. However, mathematical modeling of purification processes showed that for this type of raw material, the purification cost coefficient is 2.5–3.2 times higher compared to vegetable oils (Sun et al., 2016; Abhilash & Thomas, 2019).

The chemical composition of various types of raw materials and its effect on the quality of glycerol

Detailed analysis of the chemical composition of various raw materials using gas chromatography with mass spectrometric detection (GC–MS) and Fourier transform infrared spectroscopy (FT–IR) allowed the identification of more than 120 individual impurity compounds (Herrera-González et al., 2019; Valdés-García et al., 2024). Statistical analysis of the results allowed the classification of these compounds into 10 main groups according to their chemical nature and impact on the quality of the final product (Table 3).

The results of quantitative analysis of impurities in different types of raw materials, conducted by GC–MS method, showed that the content of fatty acids in crude glycerin from vegetable oils is 0.8–2.5% (w/w), while in glycerin from biodiesel production, this indicator can reach 6–15% (w/w). The concentration of methanol in crude glycerin of biodiesel origin is 8–25% (w/w), which is 160–500 times higher than the maximum allowable concentration for pharmacopoeial glycerin (Nagata et al., 2021; Chen et al., 2022).

Table 3
Typical impurities in various types of raw materials and their effect on the quality of glycerol

Type of impurity	Source	Impact on quality	Removal methods	Maximum permissible concentration for pharmacopeia glycerol, % (wt.)
Fatty acids	Vegetable oils, animal fats	Change in organoleptic indicators, decrease in pH	Neutralization, distillation	0.10
Methanol	Biodiesel production	Toxicity–compliance with pharmacopeia requirements	Vacuum distillation, evaporation	0.05
Salts of inorganic acids	Biodiesel production, hydrolysis processes	Decreased purity, catalysis of adverse reactions	Ion exchange, precipitation	0.01
Catalysts (NaOH, KOH)	Biodiesel production	Change in pH and incompatibility with some applications	Neutralization, precipitation	0.002
Water	All sources	Dilution, decrease in concentration	Vacuum distillation, membrane technologies	0.50
Phospholipids	Vegetable oils	Formation of emulsions, complications of cleaning	Degumming process, adsorption	0.003
Sulfur-containing compounds	Rapeseed oil, animal fats	Foul odor, oxidation catalysis	Adsorption with activated carbon	0.002
Dyes, pigments	Vegetable oils	Product Color	Bleaching, adsorption	Absence (Hazen chromaticity ≤10)
Protein impurities	Animal fats, microbiological synthesis	Foaming reduced stability	Heat treatment, filtration	0.001
Heavy metals	Catalysts, equipment	Toxicity, catalysis, oxidation	Chelation, ion exchange	Pb ≤ 0.00005; As ≤ 0.00001; Hg ≤ 0.000005

Note: source: Valdés–García et al. (2024), Herrera–González et al. (2019).

According to the results of thermogravimetric analysis and differential scanning calorimetry, it was established that raw materials of plant origin, especially refined vegetable oils, are the most suitable for obtaining glycerin of pharmacopoeial purity (99.5% and higher), since the activation energy for impurity removal processes (Ea) for these raw materials is 42–58 kJ/mol, while for glycerin of biodiesel origin this indicator is 68–92 kJ/mol (Luo et al., 2016; Lu et al., 2025).

Kinetics and mechanisms of processes for obtaining glycerol from different types of raw materials

Obtaining glycerin from raw materials of plant origin. Hydrolysis of triglycerides. Triglyceride hydrolysis is one of the most common methods for obtaining glycerol from vegetable oils. Kinetically, this process occurs in three successive stages (Choudhary et al., 2024):

$$C_3H_5(OCOR)_3 + 3H_2O \rightarrow C_3H_5(OH)_3 + 3RCOOH,$$

where, $C_3H_5(OCOR)_3$ – triglyceride (R – fatty acid hydrocarbon chain), H_2O – water, $C_3H_3(OH)_3$ – glycerol (glycerol), RCOOH – free fatty acids.

At each stage, one molecule of fatty acid is cleaved to form the corresponding salt (soap) during alkaline hydrolysis. The kinetic equation for alkaline hydrolysis is of the form (Choudhary et al., 2024):

$$-d[TG]/dt = k_1[TG][OH^-],$$

the rate of the reaction depends on the concentration of triglycerides [TG], the concentration of alkali $[OH^-]$, and the rate constant k_1, which depends exponentially on temperature according to the Arrhenius equation (Choudhary et al., 2024):

$$k_1 = A \cdot e^{\frac{-E_a}{RT}}$$

where E_a – activation energy (typically 50–60 kJ/mol for alkaline hydrolysis), R – universal gas steel, T – absolute temperature.

In industrial hydrolysis, the process is carried out at a temperature of 220–260 °C and a pressure of 2–5 MPa, which makes it possible to achieve a triglyceride conversion rate of up to 98–99% in 2–3 hours (Peterson et al., 2024).

Transesterification of vegetable oils. In the production of diesel biofuels, glycerol is obtained as a by-product of the transesterification reaction. The mechanism includes three reversible reactions (Mushtruk et al., 2022):

$$\text{Triglyceride} + ROH \rightleftharpoons \text{Diglyceride} + RCOOR_1$$
$$\text{Diglyceride} + ROH \rightleftharpoons \text{Monoglyceride} + RCOOR_2$$
$$\text{Monoglyceride} + ROH \rightleftharpoons \text{Glycerin} + RCOOR_3$$

where R – alkyl group of alcohol (usually methyl or ethyl), R_1, R_2, R_3 – fatty acid residues.

The efficiency of the process depends on the molar ratio of alcohol to oil (usually 6:1 or 9:1 for methanol), the concentration of the catalyst (0.5–1.5% by weight of the oil), the temperature, and the intensity of mixing.

Obtaining glycerol from animal fats. The mechanisms for obtaining glycerol from animal fats are similar to the processes with vegetable oils, but the kinetics have certain features:

– higher content of saturated fatty acids, which reduces solubility in alcohols;

– the presence of free fatty acids, which requires preliminary neutralization during alkaline transesterification;

– higher melting point, which requires higher process temperatures;

– for animal fats, the hydrolysis activation energy is 65–75 kJ/mol, and the transesterification rate constants are 20–30% lower than vegetable oils under the same conditions.

Synthetic obtaining of glycerol from propylene. A multi-stage process is usually used for the synthetic production of glycerol from propylene. Here are the main steps in this process (Yateem et al., 2013):

– chlorination of propylene to allyl chloride (CH_2=CH–CH_2Cl);

– hydrochlorination of allyl chloride to produce glycerol chlorohydrin (CH_2Cl–CHOH–CH_2Cl);

– hydrolysis of glycerol chlorohydrin by alkali to epichlorohydrin (CH_2OCH–CH_2Cl);

– hydrolysis of epichlorohydrin to glycerol (CH_2OH–CHOH–CH_2OH).

Alternative, more modern method (Manosak et al., 2011):

– direct oxidation of propylene to–propylene oxide using hydroperoxides or other oxidizing agents;

– hydration of propylene oxide to propylene glycol;

– additional oxidation and hydration to obtain glycerol.

Industrial synthetic production of glycerol from propylene has an advantage over the traditional method of obtaining glycerin as a by-product of soap and biodiesel production since it allows you to regulate production volumes regardless of the demand for basic products.

Microbiological synthesis of glycerol. The microbiological production of glycerol is based on the ability of some species of yeast (*Saccharomyces cerevisiae*, *Candida glycerinogenes*) and bacteria (*Bacillus subtilis*) to synthesize glycerol via the glycolytic pathway under anaerobic conditions in the presence of bisulfite (Bagheri et al., 2015).

The main metabolic pathway includes:

$$C_6H_{12}O_6 \rightarrow C_6H_{14}O_{12}P_2 \rightarrow C_3H_7O_6P \rightarrow C_3H_9O_6P \rightarrow C_3H_8O_3.$$

The process is as follows:

– glucose ($C_6H_{12}O_6$) → fructose-1,6-bisphosphate ($C_6H_{14}O_{12}P_2$)

Includes phosphorylation of both ends of the fructose molecule.

– fructose-1,6-bisphosphate ($C_6H_{14}O_{12}P_2$) → dihydroxyacetone phosphate ($C_3H_7O_6P$).

A six–carbon molecule splits into two three–carbon molecules.

– dihydroxyacetone phosphate ($C_3H_7O_6P$) → glycerol-3-phosphate ($C_3H_9O_6P$).

Reduction of the carbonyl group to the hydroxyl group using NADH:

– glycerol-3-phosphate ($C_3H_9O_6P$) → glycerol ($C_3H_8O_3$).

Removal of the phosphate group (dephosphorylation).

The kinetics of biomass growth is described by the Mono equation (Nguyen et al., 2024):

$$\mu = \mu_{max} \cdot S/(K_S + S)$$

where, μ – specific growth rate, μ_{max} – maximum specific growth rate, S – substrate concentration, K_s – saturation constant (substrate concentration at $\mu = \mu_{max}/2$).

For *Saccharomyces cerevisiae* $\mu_{max} \approx 0.3$–$0.5\ h^{-1}$, $K_s \approx 0.1$–0.2 g/L. Glycerol yield is 0.2–0.3 g/g glucose under optimal conditions.

Enzymatic processes for obtaining glycerol. Enzymatic hydrolysis of triglycerides is catalyzed by lipases of various origins (mainly from *Candida rugosa* and *Rhizomucor miehei*). Kinetics obeys the Michaelis–Menten equation (Markovski et al., 2024):

$$v = V_{max} \cdot [S]/(K_m + [S])$$

where, v – reaction speed, V_{max} – maximum speed, [S] – substrate concentration, K_m – constant Michaelis.

For lipases, *Candida rugosa*, $K_m \approx 0.5$–2.0 mmol/L, and V_{max} depends on the concentration of the enzyme and is usually 0.2–1.0 mmol/(L•min).

In contrast to chemical hydrolysis, the enzymatic process takes place under much milder conditions (30–50 °C, atmospheric pressure), which reduces energy costs and prevents the formation of by-products. However, the process speed is lower, and the cost of enzymes is higher, which limits industrial applications.

Factors affecting the kinetics of glycerol production processes. Temperature effects. For all chemical reactions to obtain glycerol, an increase in temperature increases the rate constant according to the Arrhenius equation. However, at too high temperatures (>270 °C for hydrolysis, >80 °C for transesterification), adverse reactions begin that reduce the yield and quality of glycerol (Zhang et al., 2024).

Influence of catalysts. Catalysts reduce the activation energy of reactions. In the case of transesterification:

– alkaline catalysts (NaOH, KOH): most effective for oils low in free fatty acids;

– acid catalysts (H_2SO_4, HCl): Effective for raw materials with a high content of free fatty acids;

– heterogeneous catalysts (CaO, MgO): These simplify the separation and purification of glycerol.

Mass transfer limitations. For two–phase systems (oil–water during hydrolysis, oil–alcohol during transesterification), the process speed is often limited by mass transfer at the phase interface. Intensive mixing and the use of emulsifiers increase the contact area of the phases and accelerate the reaction (Alvarez-Mateos et al., 2019).

Technological aspects of processing raw materials for the production of glycerol

Based on the analysis of literature data, a systematization of technological approaches to the processing of various types of raw materials for the production of glycerol has been carried out (Barbirato et al., 1998; Li et al., 2021). The data obtained are presented in Table 4. As shown by the analysis of data in Table 3, the most environmentally acceptable methods of glycerin production are enzymatic hydrolysis and microbiological synthesis, in which CO_2 emissions are 3–4 times lower compared to the synthetic method. The calculation of energy efficiency indicators (energy efficiency coefficient) for different technologies showed that enzymatic hydrolysis has the highest indicator (0.65–0.72), while for the synthetic method, this indicator does not exceed 0.32–0.38 (Martinez et al., 2020).

Experimental studies on the influence of technological process parameters on glycerin yield and quality showed that the optimal conditions for alkaline hydrolysis are: NaOH concentration – 8–10% (w/w), temperature – 80–90 °C, process duration – 2.5–3.0 hours. Under these conditions, the triglyceride hydrolysis degree reaches 94–96%, and the glycerin yield is 76–79% of the theoretical value (Thompson et al., 2019).

Glycerin purification methods for food and pharmaceutical applications

To achieve a level of purity that meets the requirements of pharmacopeias and food standards, raw glycerin is subjected to multi-stage purification. Table 5 presents a comparative description of the main methods of glycerol purification. Analysis of the data shows that to obtain glycerin of pharmacopoeial purity, the most effective method is a combination of purification methods that includes preliminary chemical treatment, activated carbon adsorption, and vacuum distillation (Fan et al., 2010; Ayoub & Abdullah, 2012). Quantum-chemical modeling of impurity adsorption processes on activated carbon showed that the efficiency of organic impurity removal correlates with the adsorption energy (E_{ads}), which is: for fatty acids E_{ads} = 42–58 kJ/mol; for methanol E_{ads} = 18–22 kJ/mol; for sulfur-containing compounds E_{ads} = 65–78 kJ/mol (Zheplinska et al., 2021; Vasyliv et al., 2022).

Physicochemical parameters of glycerol quality of different categories

The systematization of data from literature sources (González-Pajuelo et al., 2005; Okoye & Hameed, 2016; Thompson et al., 2019) established the key physicochemical parameters of glycerol of different quality categories, which are presented in Table 6. Analysis of the data in Table 6 shows that the requirements for pharmacopoeia glycerol are 5–10 times more stringent in all respects compared to technical glycerin, which necessitates a careful selection of both the raw material base and the purification technology (Ahmad et al., 2019; Zhang et al., 2020).

Table 4
The main technological approaches to the production of glycerin from various types of raw materials

Technology	Raw material type	Glycerin output, %	Product purity, %	Energy consumption, kWh·year/kg	Capital investments, thousand tons EUR/t·year	Environmental friendliness (CO_2 emissions, kg/t of product)
Alkaline hydrolysis (saponification)	vegetable oils, animal fats	65–80	85–90	2.8–3.5	800–1200	420–580
Enzymatic hydrolysis	vegetable oils	90–95	90–95	1.2–1.8	1500–2200	180–250
Hydrolysis under pressure	vegetable oils, animal fats	75–85	80–85	3.5–4.2	1300–1800	480–650
Transesterification in biodiesel production	vegetable oils	85–95	40–85	2.2–3.0	900–1400	250–380
Synthetic method (from propylene)	petrochemical raw materials	70–80	98–99	5.8–7.2	2500–3500	820–1100
Microbiological synthesis	sugars, food waste	40–60	70–80	1.5–2.3	1800–2500	120–220

Note: source: Alvarez-Mateos et al. (2019), Barbirato et al. (1998), Li et al. (2021).

Table 5
Comparative characteristics of glycerin purification methods

Cleaning method	Impurity removal efficiency, %	Energy consumption, kWh·year/kg	Cost, EUR/kg	Impact on product yield, %	Selectivity of impurity removal	Ecology process
Vacuum distillation	high (95–98)	2.8–3.5	0.18–0.25	decrease by (5–10)	low	average
Ion exchange	high for ionic impurities (98–99)	0.2–0.5	0.15–0.20	minimal (1–2)	high for ionic compounds	medium (resin regeneration problem)
Adsorption with activated carbon	average (65–80)	0.1–0.3	0.08–0.12	decrease by 1–3	high for organic compounds	high
Membrane filtration	high (85–95)	0.8–1.2	0.22–0.30	decrease by 2–5	high, depends on the type of membrane	high
Chemical treatment (precipitation)	average (50–75)	0.4–0.7	0.05–0.10	decrease by 3–8	low	low (waste generation)
Electrodialysis	high for ionic impurities (90–98)	1.5–2.0	0.20–0.28	decrease by 3–6	very high for ionic compounds	average
Crystallization	high (85–95)	1.8–2.5	0.15–0.22	decrease by 8–12	average	high
Combined methods	very high (98–99.8)	3.5–5.0	0.35–0.50	decrease by 8–15	high for all types of impurities	average

Note: source: Martinez et al. (2020), Thompson et al. (2019).

Table 6
Physicochemical parameters of glycerol of different quality categories

Parameter	Technical glycerin	Food-grade glycerin (E_{422})	Pharmacopoeia glycerol (USP/Ph.Eur.)	Control method
Glycerin content, %	80–95	$\geq$ 98.0	$\geq$ 99.5	gas chromatography
Density at 20 °C, g/cm^3	1.230–1.262	1.255–1.264	1.257–1.261	pycnometry
Refractive index at 20 °C	1.470–1.475	1.471–1.474	1.470–1.473	refractometry
Kinematic viscosity at 20 °C, mm^2/s	1150–1350	1200–1450	1300–1500	viscosimetry
pH (10% solution)	4.5–8.5	5.0–7.5	5.0–7.0	potentiometry
Water content, %	$\leq$ 5.0	$\leq$ 2.0	$\leq$ 0.5	titration by karl fischer
Chloride content, %	$\leq$ 0.1	$\leq$ 0.01	$\leq$ 0.001	argentometry
Sulfate content, %	$\leq$ 0.1	$\leq$ 0.01	$\leq$ 0.002	argentometry
Hazen chromaticity	$\leq$ 50	$\leq$ 20	$\leq$ 10	spectrophotometry
Heavy metal content (as Pb), %	$\leq$ 0.002	$\leq$ 0.0005	$\leq$ 0.00005	atomic absorption spectroscopy
Methanol content, %	$\leq$ 0.5	$\leq$ 0.1	$\leq$ 0.05	gas chromatography
Ethanol content, %	$\leq$ 0.5	$\leq$ 0.1	$\leq$ 0.05	gas chromatography
Organic impurities (total content), %	$\leq$ 3.0	$\leq$ 0.5	$\leq$ 0.1	gas chromatography
Fatty acid content (as oleic), %	$\leq$ 1.0	$\leq$ 0.2	$\leq$ 0.1	titration
Transmittance at 270 nm, %	not regulated	$\geq$ 80	$\geq$ 95	spectrophotometry

Note: source: González-Pajuelo et al. (2005), Okoye & Hameed (2016), Thompson et al. (2019).

Pharmacopoeia requirements for glycerol

Analysis of pharmacopeia requirements for glycerol (Jain & Patel, 2021; Mendes et al., 2023; Nagata et al., 2024) showed the existence of strict quality criteria that glycerin must meet for pharmaceutical use (Table 7). Based on the research results presented in Table 7, it was established that the strictest requirements for glycerin are set by the United States Pharmacopeia (USP) regarding active substance content (99.0–101.0%) and the Japanese Pharmacopeia (JP) regarding heavy metal content (≤1 ppm). All pharmacopeias pay special attention to controlling the content of potentially toxic impurities, such as diethylene glycol and ethylene glycol, acrolein, heavy metals, and bacterial endotoxins. Requirements for glycerin intended for the production of parenteral dosage forms are even more stringent and include additional parameters, such as sterility, absence of pyrogens, and low endotoxin content.

Table 7
Basic pharmacopeia requirements for glycerol

Indicator	European Pharmacopoeia (Ph. Eur.)	Pharmacopoeia United States (USP)	British Pharmacopoeia (BP)	Japanese Pharmacopoeia (JP)
Content of the main substance, %	98.0–101.0	99.0–101.0	98.0–101.0	≥98.0
Relative density (20 °C)	1.255–1.264	1.249–1.264	1.255–1.264	1.255–1.264
Refractive index	1.470–1.475	1.470–1.475	1.470–1.475	1.470–1.475
Water content, %	≤2.0	≤5.0	≤2.0	≤2.0
Aldehyde content, ppm	≤10	≤10	≤10	≤10
Heavy metals, ppm	≤5	≤5	≤5	≤1
Chlorides, ppm	≤10	≤10	≤10	≤10
Sulfates, ppm	≤20	≤20	≤20	≤20
Diethylene glycol and ethylene glycol, %	≤0.1	≤0.1	≤0.1	≤0.1
Total content of organic impurities, %	≤0.5	≤1.0	≤0.5	≤0.5
Catalyst residues, ppm	≤2	≤2	≤2	≤2
Acetylated compounds, %	≤0.05	≤0.05	≤0.05	≤0.05
Acrolein and glucose	not detected	not detected	not detected	not detected
Fatty acids and esters, %	≤0.02	≤0.02	≤0.02	≤0.05
Sulphate ash, %	≤0.01	≤0.01	≤0.01	≤0.01
Bacterial endotoxins, IU/g	< 0.5	< 0.5	< 0.5	< 0.5

Note: source: Jain & Patel (2021), Mendes et al. (2023), Nagata et al. (2024).

The harmonized ICH Q3C standard also establishes requirements for residual amounts of organic solvents in glycerin intended for pharmaceutical use. In particular, the methanol content should not exceed 3000 ppm, isopropanol – 5000 ppm, and acetone – 5000 ppm.

To achieve the pharmacopeia quality of glycerol, a combination of different purification methods is usually used (Roberts et al., 2021; Zhang et al., 2022). A typical sequence of purification processes for crude glycerin obtained as a by-product of biodiesel production includes the following:

– preliminary treatment (neutralization, separation of fatty acids);
– vacuum distillation for methanol removal;
– ion exchange purification for salt removal;
– adsorption purification using activated carbon;
– high-degree vacuum distillation to obtain glycerin of the required purity.

Additional purification by special methods (membrane filtration, molecular distillation) to achieve pharmacopeia quality.

The effectiveness of various purification methods significantly depends on the composition of the initial raw material and the content of specific impurities. For example, ion exchange purification is most effective for removing inorganic salts from crude glycerin from biodiesel production, while adsorption purification with activated carbon is better suited to removing organic impurities and colored compounds from glycerin obtained from animal fats (Schmidt et al., 2020).

Innovative technologies, such as supercritical fluid extraction and molecular distillation, although costly, provide the best quality of the final product and are especially effective for the production of pharmaceutical-grade glycerin. Kinetic patterns and mechanisms of glycerin production processes determine the optimal technological parameters, which, in turn, affect the economic efficiency of production and the quality of the target product.

Economic aspects of glycerol production

The economic efficiency of glycerin production depends on many factors, including the cost of raw materials, purification costs, production scale, and the quality of the final product (Foster et al., 2022; Turner et al., 2022; Rodrigues et al., 2023). The analysis of economic indicators for glycerin production from various raw material sources is presented in Table 8. The most cost-effective source of raw materials for glycerin production is biodiesel production byproducts, despite the high purification costs. Synthetic glycerin and glycerin obtained through microbiological synthesis have the highest production costs but provide a high–quality product, which is especially important for pharmaceutical applications. The profitability of pharmaceutical glycerin production is higher than that of technical glycerin for all types of raw materials, which is explained by the significantly higher market price of pharmaceutical glycerin. As of 2024, the average market prices for various types of glycerin were (Santibañez et al., 2024): technical glycerin (80–90%) – $1000–1500/ton; food-grade glycerin (>95.5%) – $1800–2300/ton; pharmaceutical glycerin USP/EP (>99.0%) – $2500–3200/ton; high–purity glycerin (>99.7%) – $3200–4000/ton.

Table 8
Economic indicators of glycerin production from various sources of raw materials

Indicator	Animal fats	Vegetable oil	Biodiesel by-products	Synthetic glycerin	Microbiological synthesis
Cost of raw materials, $/t of product	800–1000	1500–2000	100–300	1500–2000	1200–1800
Capital expenditures, $ million for a plant with a capacity of 10000 tons/year	15–20	12–18	8–15	25–35	20–30
Operating costs, $/t of product	300–400	250–350	500–800	400–600	600–900
Cleaning costs, % of total costs	20–25	15–20	40–60	5–10	25–35
Cost of technical glycerin (80–90%), $/t	1200–1500	1800–2200	700–1200	2000–2500	1800–2500
Cost of pharmaceutical glycerol (>99%), $/t	2000–2500	2500–3000	1500–2200	2800–3500	2800–3800
Profitability of production of technical glycerin, %	10–15	5–10	20–30	0–5	0–5
Profitability of pharmaceutical glycerol production, %	15–20	20–25	25–35	10–15	5–10

Note: source: Foster et al. (2022), Turner et al. (2022), Rodrigues et al. (2023).

The dynamics of global glycerin prices over the past 20 years have been characterized by significant fluctuations related to changes in the structure of the raw material base and the development of the biodiesel industry. In particular, the active expansion of biodiesel production in 2005–2010 led to market saturation with crude glycerin and a drop in prices for technical glycerin from $1800–2000/ton to $500–700/ton (Kowalski et al., 2020; Nguyen et al., 2022). Subsequently, the development of technologies for processing crude glycerin and the growing demand for high-quality glycerin from the pharmaceutical and food industries contributed to price stabilization.

Prospects for raw material base development in Ukraine

An assessment of Ukraine's potential for developing its raw material base for glycerin production showed significant opportunities (Table 9).

Table 9
Potential for Raw Material Base Development for Glycerin Production in Ukraine

Raw material type	Potential volume of glycerol production (thousand tons/year)	Available raw material base	Degree production development*	Perspective**
Sunflower oil	35–45	Enterprises of the fat and oil industry	3	5
Rapeseed oil	15–20	Enterprises of the fat and oil industry	2	4
Soybean oil	5–10	Enterprises of the fat and oil industry	2	3
Animal fats	2–5	Meat processing enterprises	1	2
Crude biodiesel glycerin	8–15	Biodiesel plants (potential for development)	1	4
Microbiological synthesis	1–3	Biotechnology enterprises	1	3
Lignocellulosic biomass	5–8	Agricultural and forestry waste	0	3
Seaweed	<1	Experimental production	0	2

Notes: source: Yang et al. (2019), Roberts et al. (2021), Zhang et al. (2022); * – degree of production development: 0 – none, 1 – initial level, 2 – limited production, 3 – developed production; ** – score from: 1 – low to 5 – high.

Environmental aspects of glycerin production

The environmental assessment of various raw material sources and glycerin production technologies is a crucial aspect in the context of sustainable development and minimizing negative environmental impact (Zhang et al., 2020; Martinez et al., 2021). A comparative environmental profile of different raw material sources is presented in Table 10. Analysis of scientific papers (Yang et al., 2019; Roberts et al., 2021; Zhang et al., 2022) shows that from an environmental perspective, the most favorable raw material sources for glycerin production are algae, lignocellulosic biomass, and biodiesel production by-products, which are characterized by the lowest carbon footprint and efficient use of land resources. Synthetic glycerin has the worst environmental indicators due to the use of non-renewable resources and high energy consumption.

Table 10
Environmental characteristics of various sources of raw materials for the production of glycerin

Indicator	Animal fats	Vegetable oils	Biodiesel by-products	Synthetic glycerin	Microbiological synthesis	Lignocellulosic biomass	Seaweed
Carbon footprint, kg CO_2–eq./kg glycerol	4.5–6.0	2.8–4.2	1.2–2.5	7.0–9.5	1.5–3.0	1.0–2.0	0.5–1.5
Water consumption, m^3/t glycerol	25–40	40–60	10–25	20–35	80–120	15–30	100–150
Energy consumption, GJ/t glycerol	18–25	15–22	12–20	30–40	20–30	15–25	18–28
Eutrophication potential, kg PO_4–eq./t glycerol	8–15	12–20	3–8	2–5	5–10	3–7	4–9
Land use, ha·year/t of glycerol	0.4–0.8	0.6–1.2	0.1–0.3	<0.1	0.1–0.2	0.2–0.4	<0.1
Use of non–renewable resources*	2	2	1	5	1	1	1
Waste toxicity*	3	2	3	4	1	2	1
Biodegradability of waste*	5	5	4	2	5	5	5

Note: source: Zhang et al. (2020), Martinez et al. (2021); * – rated from 1 (best) to 5 (worst).

The use of biodiesel production by-products as raw materials for glycerin production is particularly promising from an environmental perspective, as it allows for waste utilization and reduces the overall environmental impact of biodiesel production (Mushtruk et al., 2020). However, the process of purifying crude glycerin to pharmacopeial quality can have a significant environmental impact due to the use of chemical reagents and the energy-intensive nature of the process.

The environmental efficiency of glycerin production can be improved by implementing the following measures:

– using renewable energy sources in the production process;
– optimizing purification processes to reduce the use of chemical reagents;
– developing closed water consumption cycles;
– utilizing and recycling production waste.

Life Cycle Assessment (LCA) of glycerin produced from various raw material sources shows that using products and wastes (crude glycerin from biodiesel production, lignocellulosic biomass) typically has the lowest overall environmental impact, despite more energy-intensive purification processes.

Ukraine, being one of the world leaders in sunflower oil production (over 6 million tons per year), has significant potential for developing its own high-quality glycerin production. Specifically, processing 1 ton of sunflower oil can yield about 100 kg of glycerin, which means that using even 10% of the sunflower oil produced in Ukraine for glycerin production would allow obtaining about 60 thousand tons of product per year (Mushtruk et al., 2021).

A promising direction is also the development of biodiesel production from rapeseed oil, which will allow crude glycerin to be obtained as a by-product. The potential for biodiesel production in Ukraine is estimated at 100–150 thousand tons per year, corresponding to 10–15 thousand tons of crude glycerin.

The main advantages of Ukraine for developing glycerin production are:

– developed raw material base (sunflower, rapeseed, soybean oils);
– availability of qualified specialists and scientific institutions;
– geographical location providing access to the European market;
– relatively low production costs;
– significant export potential.

The main problems hindering the development of glycerin production in Ukraine are:

– insufficient development of oilseed processing infrastructure;
– limited investments in high–tech production;
– insufficient level of biodiesel industry development;
– lack of state support for biofuel production;
– difficulties with product certification according to international standards.

To realize Ukraine's potential in high–quality glycerin production, it is necessary to:

– develop integrated productions that combine oilseed processing, biodiesel production, and glycerin purification;

– implement modern technologies for purifying glycerin to pharmacopeial quality;

– develop cooperation between manufacturing enterprises and research institutions;

– promote investment in high-tech production;

– provide state support for biofuel production and related products.

Analyzing current research and developments in glycerin production allows us to identify several innovative directions with significant potential for expanding and optimizing the raw material base:

– genetically modified microorganisms for glycerin biosynthesis: development of microorganism strains with increased glycerin synthesis productivity and the ability to use various substrates, including agricultural and food industry waste;

– integrated biorefineries: creating complex productions that combine biomass processing, biofuel production, and the extraction of glycerin and other valuable chemical compounds within a single technological process;

– catalytic processes for converting carbohydrates to glycerin: developing new catalysts and processes for the direct conversion of cellulose, starch, and other carbohydrates into glycerin with high yield and selectivity;

– photobioreactors for algae cultivation: developing efficient systems for the mass cultivation of algae with high lipid content, which can be converted into glycerin;

– "green" technologies for glycerin purification: developing environmentally safe methods for glycerin purification that utilize biocatalysts, membrane technologies, and other "green" approaches instead of traditional chemical methods;

– electrochemical methods for glycerin synthesis and purification: employing electrochemical processes for glycerin synthesis from renewable raw materials and for the purification of crude glycerin with minimal use of chemical reagents;

– valorization of crude glycerin: developing comprehensive approaches to processing crude glycerin from biodiesel production to obtain not only purified glycerin but also other valuable products such as organic acids, bioplastics, and polymers;

– synthesis of glycerin from CO_2: researching the possibilities of catalytic or biological conversion of CO_2 to glycerin, which will simultaneously address the problem of carbon dioxide utilization and the creation of a valuable chemical product.

These innovative directions are at different stages of development and implementation – from laboratory research to pilot installations but hold significant potential for transforming the raw material base of glycerin production shortly.

Discussion

Analysis of literature sources demonstrates significant discrepancies in evaluating the effectiveness of different types of raw materials for producing food-grade and pharmaceutical–quality glycerin. Several researchers (Jitchaiyapoom et al., 2024; Sułkowski et al., 2018; Luo et al., 2021) believe that the most promising direction is developing effective methods for purifying glycerin obtained as a by-product of biodiesel production, as this addresses both economic and environmental problems simultaneously. However, studies by Yang et al. (2012) and Park et al. (2022) point to fundamental limitations of this approach due to the difficulty in achieving consistently high quality of the final product given the variability in the composition of the raw materials.

Studies employing chemometric analysis, conducted by Davis et al. (2018), established a correlation between the chemical composition of raw materials and the effectiveness of various purification methods. The authors proposed a mathematical model to predict the optimal glycerin purification strategy based on impurity composition data. However, works by Ahmed et al. (2022) and Agarwal & Mishra (2023) show that this model has limited accuracy at high catalyst concentrations in biodiesel-derived glycerin.

Particularly intense discussions arise regarding the use of animal-derived waste as raw material for producing pharmaceutical–grade glycerin. While Li et al. (2019) and Kato et al. (2021) demonstrate the potential for obtaining high-quality glycerin from this raw material, provided advanced purification technologies are employed, Schmidt et al. (2020) categorically deny this possibility due to fundamental limitations associated with removing specific biological impurities.

An interesting approach is proposed in the works of Liu et al. (2023) and Jitchaiyapoom et al., 2024, who investigated targeted microbiological synthesis of glycerin using modified microorganism strains. The authors established that cultivating *Yarrowia lipolytica* on a glucose medium under carbon excess and nitrogen deficiency conditions yields glycerin at 0.22 g/g of substrate, which is 1.8 times higher than the wild strain. IR-spectroscopic analysis of the product showed the absence of many typical impurities characteristic of glycerin from traditional sources, simplifying further purification.

Thompson et al. (2019) conducted a comparative study on the economic efficiency of various technologies for producing pharmacopeial quality glycerin through life cycle modeling. The results revealed that, at current raw material and energy prices, glycerin obtained as a by-product of biodiesel production is the least expensive (1.2–1.5 EUR/kg); however, considering the purification costs to achieve pharmacopeial quality, the price increases to 2.8–3.2 EUR/kg, approaching that of glycerin derived from vegetable oils (3.0–3.5 EUR/kg).

Analysis of methodological approaches used in glycerin raw material studies revealed several significant limitations. First, most studies (Kaushik & Reddy, 2023; Kim et al., 2024) focus on the technological aspects of processing specific raw materials without a comprehensive comparative analysis of alternative sources. Second, the economic assessments presented in works (Ibrahim et al., 2020; Johnson et al., 2024) often overlook the dynamics of raw material and energy prices, significantly reducing their predictive value.

Roberts et al. (2021) critically analyzed the methods used to assess glycerin quality in various studies and noted the absence of a standardized approach. The authors proposed a comprehensive assessment methodology that incorporates both chromatographic methods (HPLC, GC–MS) and spectroscopic methods (FT–IR, NMR), enabling complete characterization of glycerin's chemical composition and predictions regarding its suitability for various applications.

A significant drawback of many studies is the absence of long–term stability tests for purified glycerin. Kim et al. (2021) showed that glycerin obtained from biodiesel raw materials, even after thorough purification, tends to change its physicochemical parameters during long-term storage, unlike glycerin from traditional sources.

Based on the conducted analysis, several promising directions for developing the raw material base for food-grade and pharmaceutical–quality glycerin production can be identified:

Development of selective adsorbents for effective removal of specific impurities from glycerin of biodiesel origin. Wang et al. (2024) developed a modified zeolite with a functionalized surface that demonstrates selective adsorption of methanol and catalysts with a removal efficiency of up to 98.5%.

Creation of integrated productions where the processes of biodiesel production and glycerin purification are technologically linked. Alvarez-Mateos et al. (2019) proposed a technological scheme using heterogeneous catalysts and continuous distillation, which allows food-grade glycerin to be obtained directly in the process of biodiesel production with minimal energy costs.

Use of enzymatic technologies for selective hydrolysis of vegetable oils to obtain high-purity glycerin. Using NMR spectroscopy, Luo et al. (2021) showed that glycerin obtained through the enzymatic hydrolysis of oils contains an order of magnitude fewer impurities compared to glycerin obtained by traditional chemical methods.

Development of hybrid membrane technologies for continuous glycerin purification. Park et al. (2022) proposed a combination of ultrafiltration and nanofiltration with subsequent ion exchange, which allows pharmacopeial quality glycerin to be obtained with a yield of 92–94% at energy costs 30–40% lower compared to traditional methods.

Development of technologies for microbiological synthesis of glycerin using food industry waste as a substrate. Cheng et al. (2007) demonstrated the possibility of using modified strains of *Escherichia coli* for glycerin synthesis from sugar–containing waste with productivity up to 45 g/L•h.

The conducted analysis of economic aspects of glycerin production from various raw materials shows that glycerin obtained as a by-product of biodiesel production has the lowest cost. However, as noted by Turner et al. (2022), economic efficiency significantly decreases when it is necessary to bring the product quality to the level of pharmacopeial requirements due to high purification costs.

From an environmental perspective, the most acceptable approach is the use of food production waste and biodiesel production products, as this allows for waste utilization and reduces environmental pollution. Life cycle analysis conducted by Harris et al. (2019) showed that the carbon footprint in glycerin production from waste is 2.1–2.8 kg CO_2-eq./kg of product, while for synthetic glycerin, this indicator reaches 5.8–7.2 kg CO_2-eq./kg.

Econometric modeling conducted by Foster et al. (2022) established optimal criteria for selecting raw material sources for glycerin production of various quality categories depending on the ratio of prices for raw materials and energy. The authors developed a decision-making algorithm that allows prompt adjustiment of production strategy when market conditions change.

Based on the analysis of the raw material base for food and pharmacological glycerin production, promising directions for future research include the development of innovative methods for processing oil and fat industry waste using enzymatic catalysis and "green" solvents. It also seems appropriate to research new sources of raw materials, particularly microalgae and biofuel industry waste, which will enhance the environmental sustainability of production and reduce its cost while maintaining a high quality of the final product.

An important direction is also the improvement of methods for purification and standardization of pharmacological glycerin to meet the requirements of modern pharmacopeias and regulatory documents. The development of complex technologies that allow one to simultaneously obtain high-purity glycerin and accompanying valuable components seems promising, as it will contribute to increasing the economic efficiency of production and expanding the range of products in the market of pharmaceutical and food ingredients.

Conclusion

The comprehensive analytical review of the raw material base for the production of food and pharmacological glycerin concludes that vegetable oils, particularly palm, coconut, and rapeseed oils, along with products from biodiesel production, exhibit the greatest potential as long-term raw material sources. These sources have an optimal balance of final product quality indicators, economic efficiency, and environmental safety in the production process. Predictive analysis suggests a likely increase in the share of these raw material components within the overall structure of glycerin production over the next decade.

It has been established that the most effective method to obtain pharmacopeial quality glycerin (99.5% and higher) employs a combined purification strategy comprising preliminary chemical treatment, adsorption purification with activated carbon, and vacuum distillation. This technological sequence ensures the removal of key contaminant groups: fatty acids, methanol, salt inclusions, catalysts, and pigment compounds. In the medium term, over the next 5–7 years, modernization of these processes is expected through the introduction of automated systems and optimization of energy costs.

Based on experimental data, it has been determined that the main critical quality parameters of raw materials affecting the ability to obtain pharmacopeial and food-grade glycerin include initial glycerin concentration, the presence of heavy metal compounds, sulfur-containing derivatives, and protein contaminants, which are characterized by low removal efficiency when conventional purification methods are used. By 2035, the development of analytical methods with enhanced sensitivity for detecting micro-quantities of these compounds is anticipated.

Econometric analysis indicates that glycerin production as a by-product of biodiesel production will retain the highest economic efficiency in the coming decade. However, achieving high-quality product characteristics necessitates substantial capital investments in purification processes, which diminishes overall profitability. Over the next decade, advancements in more efficient purification technologies are expected to reduce these costs by 15–20%.

In the long term, up to 2035, promising directions for high-purity glycerin production technologies include enzymatic methods for vegetable oil hydrolysis, hybrid membrane purification systems, and integrated production complexes, which show the greatest potential. These innovative approaches provide synergy between biodiesel production and high-quality glycerin while minimizing energy consumption and environmental impact. According to expert estimates, by 2030, the share of such technologies in the overall production structure may reach 30–40%.

The need for developing and implementing standardized glycerin quality control methods, particularly for identifying specific impurities, has been substantiated. The adoption of these methods will allow an objective evaluation of the suitability of various raw material types for pharmaceutical glycerin production and enable predictions regarding new promising raw material sources. By 2030, the ratification of international quality standards is expected, considering the specifics of different raw material sources and technological production processes.

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