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Evaluation of the quality indicators of food-grade glycerin derived from different oil/fat raw materials

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ABSTRACT

The relevance of the research is determined by the growing demand for food-grade glycerin and the need for an objective, comprehensive assessment of its quality. In modern domestic and global food technologies, glycerin-containing products are characterized by a wide range of functional properties: it is used as a sweetener in confectionery, an emulsifier to prevent the stratification of fat systems, a solvent for uniform distribution of biologically active components, as well as as a safe additive in the production of beverages, alcoholic beverages, pasta and dried fruits. The combination of these properties gives glycerin a significant place not only in the European but also in the global market for the food and processing industry. In this regard, the priority research area is the improvement of approaches to assessing product quality by comprehensively analyzing its properties. The purpose of this study is to determine the quality of glycerin-containing products obtained from oil and fat raw materials using the developed mathematical models of polygons for numerical analysis. The assessment was carried out using a set of indicators, including color, relative density, density at 20 °C, reaction to an alkaline medium, mass fractions of glycerin and ash, and the saponification coefficient. This enabled the formation of dimensionless complexes and the numerical analysis of the compliance of the studied samples with regulatory requirements. Experimental data processing and the calculation of quality criteria were performed using programming methods and the Excel environment, enabling us to develop geometric quality models and determine the required parameters for calculations. According to the studies, samples obtained from technical animal fats and rapeseed oil do not meet regulatory requirements, exceeding the average quality indicators by more than 3.5 times. Instead, the best characteristics were demonstrated by samples of sunflower and soybean oil, which correspond to the maximum regulatory values, while the average indicators exceeded the regulatory values by 14% to 24%. The proposed mathematical models can be effectively used to assess the condition of objects of varying complexity, provided that a wide range of physical, mechanical, chemical, and biological characteristics is considered, thereby ensuring the objectivity and scientific validity of the results.

Keywords: food-grade glycerin, quality, raw materials, regulatory characteristics, planar geometric models, factor space, evaluation criteria

INTRODUCTION

The spread of production of glycerin-containing products in modern food technologies is due to the complex of its functional and technological properties. Food glycerin is widely used as an effective sweetener in confectionery products (candy, glazes, mastics, ice cream, alcoholic beverages) **[1]**, and **[2]**, as an emulsifier that prevents phase separation of fat-water systems, and as a universal solvent for aromatic and biologically active components, ensuring their uniform distribution in food matrices. In addition, glycerin is used as a safe food

additive in a wide range of products (beverages, flour and pasta products, dried fruits, etc.) **[3]**, and **[4]**. Due to its pronounced hygroscopic properties, glycerin can regulate the water activity of products, thereby extending their shelf life and stabilizing quality **[5]**, and **[6]**.

In the current context of development of the agro-industrial complex and the growth in the processing volumes of oil and fat raw materials, particularly soybean, rapeseed, and sunflower oils, the production of glycerin is becoming particularly relevant as a by-product and an important component of the food and bioenergy industries **[7]**, and **[8]**. The quality of glycerin significantly depends on the properties of the raw materials, the technological parameters of its processing, and the conditions of purification and storage. At the same time, the variability of these factors makes it difficult to ensure stable quality indicators of the final product **[9]**, and **[10]**.

Traditional approaches to assessing the quality of glycerin-containing products, particularly organoleptic methods, are characterized by subjectivity and limited ability to account for the full range of physicochemical parameters **[11]**. This necessitates the use of modern methods of mathematical and multifactor analysis, which allow the integration of heterogeneous indicators into a single evaluation system and ensure the objectivity of the results. One of the promising approaches is the use of polygonal models (polygon models) within the framework of the "factor area" method, which allows for comprehensive identification of product quality, comparative analysis of samples, and justification of optimal technological solutions **[12]**.

The purpose of this study is to assess the quality state of food glycerin obtained from oil and fat raw materials, based on a multifactor analysis of its characteristics using geometric models in the form of polygons. The proposed approach involves the formation of dimensionless evaluation parameters, the construction of factor areas, and the determination of integral quality indicators for predicting the properties of the final product.

To achieve the set goal, the key quality indicators of glycerin-containing products were analyzed, normalized to dimensionless values, geometric models of the quality state for the studied samples were constructed, and the models were compared. The main evaluation characteristics include color number, relative density (relative to water), density at 20 °C, reactivity in acidic and alkaline environments (HCl, KOH), mass fractions of pure glycerin and ash, as well as saponification coefficient, which together provide a comprehensive assessment of the quality of the studied product.

Scientific Hypothesis

This study hypothesizes that transforming key physicochemical quality indicators of glycerin-containing products into dimensionless variables and representing them as polygonal factor areas constitutes a robust, statistically valid framework for integrated quality assessment. The geometric characteristics of the constructed polygons, specifically area, shape, and proportionality, are expected to quantitatively reflect the overall quality level of glycerin derived from oil and fat raw materials and its compliance with established regulatory standards.

It is further hypothesized that the polygonal factor area serves as an integral descriptor that captures the combined effect of multiple quality parameters, including color index, density, ash content, glycerol content, and saponification coefficient. The proposed approach is expected to reduce dimensionality while preserving the system's essential variability, thereby enabling improved discrimination among samples and enhanced sensitivity to deviations from standard specifications.

The null hypothesis (H_0) states that no statistically significant relationship exists between the polygonal factor area and the set of physicochemical quality indicators of glycerin-containing products ($p \geq 0.05$), and that the proposed model does not provide a statistically significant improvement in the accuracy, sensitivity, or integrative capacity of quality assessment compared to conventional evaluation methods.

The alternative hypothesis (H_1) states that a statistically significant relationship exists between the polygonal factor area and the combined set of physicochemical quality indicators ($p < 0.05$), and that the proposed model provides a statistically significant improvement in the objectivity, sensitivity, and integrative performance of glycerin quality assessment.

Hypothesis testing is performed using correlation and regression analyses, including the estimation of Pearson or Spearman correlation coefficients, multiple regression models, and analysis of determination coefficients (R^2). Statistical significance is evaluated using appropriate hypothesis-testing procedures at a 95% confidence level.

Objectives

The objective of this study is to develop and experimentally validate a mathematical model describing the relationship between the physicochemical quality indicators of glycerin-containing products and the key technological factors influencing their formation.

Specifically, the study aims to (I) quantify the effect of selected processing parameters (production and purification conditions) on glycerin quality, (II) identify the most significant factors affecting quality indicators, and (III) assess the applicability of a polygon-based multifactor model for integrated quality evaluation using experimental data obtained from glycerin samples derived from oil and fat raw

MATERIAL AND METHODS

Samples

Samples description: For the experimental study, five glycerin samples of different origins were used. All samples were obtained via transesterification of oil and fat raw materials, followed by purification in accordance with DSTU 4553:2006 **[13]**to achieve food-grade quality. The samples included: glycerin derived from technical animal fats, glycerin derived from waste cooking oils, glycerin derived from rapeseed oil, glycerin derived from sunflower oil, and glycerin derived from soybean oil.

Despite the different origins of the raw materials, all samples were subjected to identical purification procedures and met the physicochemical requirements for food-grade glycerin as defined by the applied standard

Samples collection: Samples were taken from the total volume after the glycerol purification process and temporarily stored at 18 °C.

Samples preparation: To prepare glycerin samples for experimental studies, it is necessary to follow a standardized procedure that ensures representativeness, stability, and reproducibility of results:

• samples of glycerin-containing products were selected in such a way as to reflect the average quality level of products obtained from different types of oil and fat raw materials (sunflower, soybean, rapeseed, animal fats);

• the starting raw materials for obtaining glycerin must meet technological requirements, be cleaned of mechanical impurities, water, and associated undesirable components;

• glycerin was obtained in accordance with the accepted technology for processing oils and fats (in particular, hydrolysis or transesterification processes with subsequent purification);

• the obtained glycerin was subjected to purification (filtration, neutralization, if necessary, distillation) to remove residues of fatty acids, catalysts, salts, and other impurities that may affect the results of the studies;

• the prepared samples were stored in sealed containers under controlled temperature and humidity conditions to prevent moisture absorption, oxidative processes, and changes in physicochemical characteristics;

• before conducting the analyses, the samples were kept until temperature equilibrium was reached (20 °C), which ensures the correct determination of density and other indicators.

The proposed sample preparation sequence ensures the reliability, reproducibility, and accuracy of experimental data, which are necessary conditions for further mathematical modeling and the objective assessment of the quality of glycerol-containing products.

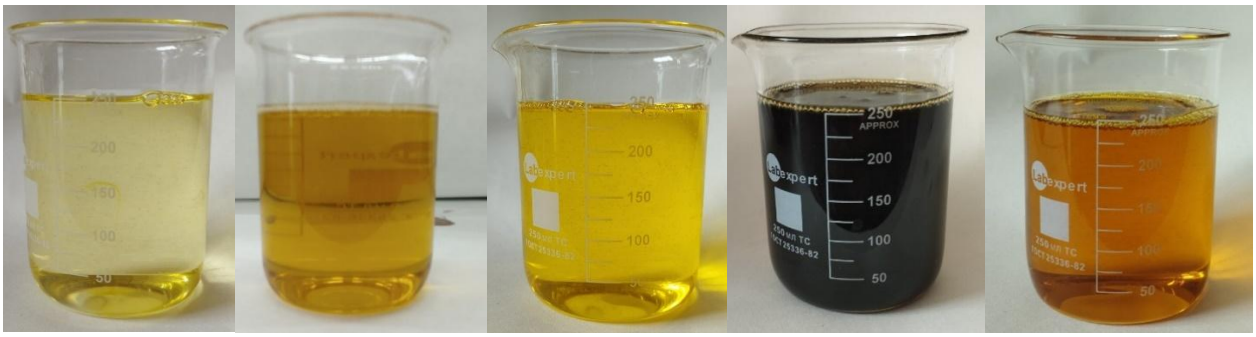
Number of samples analysed: Five types of glycerin samples of different origin were used in this study (animal fats, waste oils, rapeseed, sunflower, and soybean oil). For each type of glycerin, five independent batches were prepared and analyzed, resulting in a total of 25 samples (n = 25). All physicochemical measurements were performed in triplicate (technical replicates) for each sample, and the results are reported as mean ± standard deviation. The statistical analysis was based on the averaged values obtained from the replicate measurements. Model validation was performed using a subset of the experimental data; no external independent validation dataset was used.

Chemicals

All chemicals used in this study were of analytical grade (grade A, p.d.a.) and supplied by Khimlaborreakt (Ukraine), unless otherwise specified. The following reagents were used: sodium hydroxide (NaOH), sulfuric acid (H_2SO_4), hydrochloric acid (HCl), phosphoric acid (H_3PO_4), potassium hydroxide (KOH, alcoholic solution), activated carbon (powdered), silica gel (SiO_2), ethanol (C_2H_5OH, 96%), methanol (CH_3OH), diethyl ether ($C_4H_{10}O$), petroleum ether, phenolphthalein ($C_{20}H_{14}O_4$), methyl orange ($C_{14}H_{14}N_3NaO_3S$), universal indicator solution, potassium iodide (KI), sodium thiosulfate ($Na_2S_2O_3$), starch solution, glacial acetic acid (CH_3COOH), chloroform ($CHCl_3$), silver nitrate ($AgNO_3$), barium chloride ($BaCl_2$), nitric acid (HNO_3), and distilled water.

Animals, Plants and Biological Materials

Vegetable oils were used as raw materials for the production of glycerin: sunflower (*Helianthus annuus L.*). Figure 1a, soybean (*Glycine max (L.) Merr.*) Figure 1b and rapeseed (*Brassica napus L.*) Figure 1c, obtained by cold pressing in laboratory conditions. The selected samples were representative of industrial batches and met the quality standards for oil raw materials. The study also used technical animal fat (Figure 1d) obtained from LLC "Skvyra" (Ukraine) and waste vegetable oil from catering establishments (Figure 1e), which had been previously purified in accordance with the standard, as additional sources of lipid raw materials for glycerin production. All raw materials were stored under controlled conditions until processing to prevent degradation and maintain the stability of physicochemical parameters.



a) *b)* *c)* *d)* *e)*

Figure 1 Samples of raw materials for glycerin production.

Instruments

The following laboratory equipment was used in this study: drying cabinet and muffle furnace (SNOL), rotary evaporator (Heidolph, Germany), laboratory glass distillation unit for glycerin purification, pH meter (Hanna Instruments, model HI8314), digital thermometer (Milwaukee Instruments, model TH310), viscometer (Brookfield DV-E), densimeter (Anton Paar DMA 35), refractometer (ATAGO), analytical balance (AXIS BDM 3), magnetic stirrer with heating (LMM), centrifuge (SNOL), and standard laboratory glassware (burettes, pipettes, dispensers, and volumetric flasks).

Laboratory Methods

The physicochemical properties of the glycerin samples were determined using standardized and internationally recognized analytical procedures.

Moisture content was determined by drying to constant weight in accordance with ISO 760 (Karl Fischer method). Relative density was measured at 20 °C using a pycnometric method in accordance with ISO 12185. Kinematic viscosity was determined using a capillary viscometer in accordance with ISO 3104.

Active acidity (pH) was measured potentiometrically using a calibrated pH meter in accordance with ISO 10523. Ash content (sulfated ash) was determined by incineration in accordance with European Pharmacopeia (Ph. Eur.) 2.4.14.

The glycerol content was determined using titrimetric methods (periodate or acetin method) in accordance with the European Pharmacopeia monograph for glycerol and USP–NF requirements. The acid value was determined by titration with an alkaline solution according to ISO 660, while residual alkalinity was determined by titration with a standardized acid solution.

Inorganic impurities (chlorides and sulfates) were determined using precipitation methods in accordance with Ph. Eur. 2.4.4 (chlorides) and Ph. Eur. 2.4.13 (sulfates). Color was evaluated using spectrophotometric methods in accordance with ISO 6271 (Hazen scale).

All measurements were performed in triplicate, and the results are presented as mean ± standard deviation.

Description of the Experiment

Study flow: To investigate the qualitative characteristics of glycerin-containing products, a multivariate analysis was performed on samples from various raw materials (sunflower, soybean, rapeseed oils, and animal fats). The samples differed in processing conditions, purification methods, and storage conditions, enabling a comprehensive assessment of factors influencing glycerin quality. To ensure representativeness, glycerin samples were selected from various production batches corresponding to typical industrial conditions.

At the initial stage, each glycerin sample was subjected to detailed physicochemical analysis to determine key quality indicators, including moisture content, density, viscosity, ash content, pH, content of pure glycerin, acid and alkaline values, and the presence of inorganic impurities. Particular attention was given to parameters reflecting the degree of purification and the presence of residual contaminants, which directly affect glycerin's functional properties.

In the next stage, the obtained experimental data were transformed into dimensionless form and used for multifactor analysis. Based on these data, factorial (polygonal) models were constructed to represent the quality state of each sample in a multidimensional parameter space. The geometric characteristics of the polygons, particularly their area, were used as integral indicators of product quality.

All samples were grouped by origin and processing conditions. For each group, correlations between individual quality indicators and the integrated quality parameter (polygon area) were analyzed. This approach enabled the identification of the most significant factors affecting glycerin quality and the evaluation of each parameter's contribution to the product's overall condition.

At the final stage, the developed models were validated using independent glycerin samples, which ensured the reliability and predictive capability of the proposed method for quality assessment.

Quality Assurance

Number of repeated analyses: The study was repeated 5 times, and the experimental data were processed using statistical methods.

Number of experiment replication: Five types of glycerin were investigated. For each type, five independent batches were analyzed (n = 25). All measurements were performed in triplicate (technical replicates), and results are presented as mean ± standard deviation.

Reference materials: -

Calibration: Each instrument was calibrated before each experiment, and calibration checks were performed regularly to maintain measurement accuracy. Each instrument was calibrated before each experiment, and calibration checks were performed regularly to maintain measurement accuracy.

Laboratory accreditation: The experiments were conducted at the "Ukrainian Laboratory of Quality and Safety of Agricultural and Industrial Complex Products", the management of which is carried out through the implementation of a management system built (since 2007) by the requirements of DSTU EN ISO/IEC 17025:2019 (EN ISO/IEC 17025:2017, IDT; ISO/IEC 17025:2017, IDT) and confirmed by the Accreditation Certificate of the National Accreditation Agency of Ukraine.

Data Access

The data supporting the findings of this study are not publicly available.

Statistical Analysis

Statistical analysis was performed using Statistica 13.0 (TIBCO Software Inc., Palo Alto, CA, USA) and Microsoft Excel 365 (Microsoft Corporation, Redmond, WA, USA).

Experimental data were analyzed at the sample level**,** where each glycerin-containing product obtained from different raw materials was treated as an independent observation. No repeated-measures design was used, as each sample was evaluated once after completion of the technological treatment process.

Data preprocessing included screening for outliers using Grubbs' test $(\alpha = 0.05)$, assessing missing values, and normalizing variables to dimensionless units to ensure comparability across indicators.

The analysis focused on identifying relationships between physicochemical parameters (moisture content, density, viscosity, ash content, glycerin content, and related indicators) and the integral quality criterion defined as the polygonal model area. Descriptive statistics and comparative analysis were primarily used to evaluate differences between sample groups obtained from different raw materials.

Where appropriate, inferential statistical methods (including regression-based approaches and analysis of variance) were applied to support the interpretation of observed trends. The level of statistical significance was set at $p \leq 0.05$**.**

To assess potential redundancy among correlated variables, exploratory dimensionality reduction techniques (e.g., principal component analysis) were considered to improve data interpretability.

Given the limited dataset and the exploratory nature of the study, statistical methods were applied primarily to support trend identification and comparative evaluation**,** rather than to develop fully validated predictive models. No additional covariates were included in the analysis.

Reporting and transparency statement

The present study was conducted using a structured experimental design to ensure the reproducibility and transparency of the results. The selection of glycerin samples was intended to represent typical industrial conditions; however, randomization into experimental groups was not applied, as the study was based on predefined categories of raw materials and processing conditions. Blinding was not implemented because the physicochemical measurements were analytical in nature.

The sample size was determined based on the availability of representative industrial samples and consistency with similar studies in the field of oil and fat processing. Each experimental condition included at least three independent samples (biological replicates), and all measurements were performed in triplicate (technical replicates) to ensure the reliability of the results.

Prior to analysis, all datasets were subjected to validation procedures, including outlier and inconsistency screening. No data or samples were excluded from the final analysis, except for cases in which measurements were technically invalid due to experimental error, which were subsequently repeated.

All experimental procedures, data processing steps, and statistical analyses were carried out using standardized, widely accepted methods. The study design, data handling, and analysis approach ensure the transparency, consistency, and reproducibility of the reported results.

RESULTS AND DISCUSSION

Experimental studies were conducted with the following samples of purified glycerin:

- Glycerin from industrial animal fats, Figure 2a;
- Glycerin from rapeseed oil, Figure 2b;
- Glycerin from sunflower oil, Figure 2c;
- Glycerin from waste oils, Figure 2d;
- Glycerin from soybean oil, Figure 2e.

The initial data for modeling were obtained from experimental studies of glycerin-containing raw materials, as shown in Table 1. To conduct a qualitative and comparative assessment of the studied food glycerin raw materials, the assessment criteria were selected based on the two-sided interval of values, using the standards D-98, PK – 94, T – 94, and T – 88 (Table 1).

a *b* *c* *d* *e*

Figure 2 Experimental samples of glycerin.

Table 1 Physicochemical parameters of purified glycerin-containing raw materials.

	Indicator name	DSTU 4553:2006 [13]				Parameters for test samples				
		D-98	PK-94	T-94	T-88	1	2	3	4	5
1	Color number, mg J2 /100 cm^3 (no more)	5	1	5	5	11	5	9	0	5
2	Relative density at 20°C in relation to water, g/cm^3(not less)	1.258	1.248	1.248	1.232	1.249	1.242	1.259	1.248	1.258
3	Thickness ρ at 20 °C g/cm^3, (not less)	1.255	1.244	1.244	1.232	1.235	1.255	1.221	1.240	1.254
4	Reaction of glycerol, 0.1 mol / dm^3 of HCl or KOH solution, cm^2, (no more)	1.5	1.5	1.5	1.5	3.5	2.1	1.5	2.0	1.5
5	Mass fraction of pure glycerol, % (not less)	98	94	94	88	89	93	98	96	97
6	Mass fraction of ash, % (no more)	0.14	0.01	0.02	0.25	0.21	0.03	0.11	0.02	0.11
7	Saponification coefficient (esters), mg KOH per 1 g glycerol, (no more)	0.7	0.7	2.0	2.5	0.5	0.45	1.1	0.6	0.7

According to the results of experimental studies and normative indicators, the estimated characteristics were presented as dimensionless complexes (Table 2), obtained as the ratio of the actual i-th parameter to its normalized value **[22]**, and **[23]**. It is obvious that, for the corresponding product samples, the normative indicators were expressed numerically in dimensionless units, whereas the current ones are expressed as fractions. Considering that these characteristics determine the qualitative state of the studied glycerin samples, the geometric area defined by the specified parameters constitutes the factor space for the qualitative state of the oil product under the scientific hypothesis in the mathematical model.

Table 2 Calculation of quality parameters of glycerin from technical animal fats according to the main characteristics of products during bilateral assessment using the standard D – 98.

		Standard D - 98				**Sample quality characteristics**			
	Indicator name	**F_c**	**R, c. un.**	**F_{max}**	**f_i**	**R_i, c. un.**	**S_c, c. un.^{2}**	**S_i, c. un.^{2}**	**K_{VQ}**	**K_{VN}**
1	Color number, mg J2 /100 cm^3	2.5	1.0	5.0	2.2	**4.4**				
2	Relative density at 20°C in relation to water, g/cm³	1.24	1.0	1.258	0.993	**1.003**				
3	Density, ρ at 20˚C, g/cm³	1.24	1.0	1.255	0.984	**0.993**				
4	Reaction of glycerin, 0.1 mol/dm^3 HCl or KOH solution, cm^2	0.75	1.0	1.5	2.333	**4.667**	2.736	9.79	3.58	1.376
5	Mass fraction of pure glycerin, %	93	1.0	98	0.908	**0.957**				
6	Mass fraction of ash, %	0.07	1.0	0.14	1.5	**3**				
7	Saponification coefficient, mg KOH per 1 g glycerin	0.35	1.0	0.7	0,714	**1.43**				

Note: The following parameters were used in the table: F_c – average value of the normalized parameter being evaluated; F_{max} – maximum value of the normalized parameter; $R = 1.0$ – value of the normalized parameter in conventional units; F_i – actual value of the current parameter; R_i – current parameters presented in conventional units; S_i – factor space of current parameters, determined by the area of an irregular polygon, con. un^2; $S_н$ – normative factor space: for two-sided evaluation $S_H = S_c$, con. un^2; k_{VQ} – coefficient of compliance with a given quality interval; k_{VN} – coefficient of compliance with the limit quality standards.

When constructing geometric models, the estimated quality characteristics were laid out through the diagonals of the polygons, starting from their center. Since the values of the normalized characteristics are equal to a conventional unit, the factor space corresponding to the normative or recommended quality state is a regular polygon, the number of faces of which is determined by the number of quality criteria **[24]**, **[25]**. This area for the 7-factor space was determined by the formula:

$$S_{n7}=0,5mR^2\sin\alpha=0,5\cdot7\cdot\sin51,4=2,736\ com.un^2 \quad (1)$$

where *m is the* number of angles or sides of the polygon; $R = 1$ for normalized parameter values.

It is obvious that the area formed according to the experimental characteristics of the studied samples of glycerin-containing products is displayed in the form of an irregular polygon. Accordingly, this area constitutes the factor space of the qualitative state of the studied products, which was determined by the formula **[26]**:

$$S_{07}= 0,5\ \sin\alpha\cdot[\ R_1\cdot R_2+R_2\cdot R_3 + R_3\cdot R_4 + R_4\cdot R_5 + R_5\cdot R_6 + R_6\cdot R_7 + R_7\cdot R_1] \quad (2)$$

The algebraic ratios of the normative and actual areas of polygons were used in the given mathematical modeling as quality criteria.

To assess possible deviations of product characteristics from the limit (maximum) normative or recommended values, the proposed coefficient of conformity of the normative quality limit was used

$$k_{VN} = \frac{\sum f_i}{n} \quad (3)$$

where F_i *is* the valid value of the current parameter; F_{max} – maximum value of the normalized parameter **(Table 2)**; $f_i = F_i / F_{max}$; n – number of current parameters to be evaluated.

For a two-sided assessment using the characteristics presented in Table 1, a *coefficient of compliance with a given quality interval was developed and proposed*

$$k_{VQ} = \frac{S_i}{S_c} \quad (4)$$

where S_c is the average value of the normalized interval; S_i is the factor space of current parameters.

This evaluation criterion shows how close the complex of quality indicators of the product sample is to the normative quality interval regulated for the studied samples of glycerin-containing raw materials.

Then, according to the results of the mathematical study shown above, the desired quality assessment models for the most technologically successful sample of oil raw materials can be displayed in the form of an algorithm

$$k_{VQ} = \frac{S_i}{S_c} \rightarrow 1$$

Using the calculated values of the current parameters R_i (Table 2), we constructed a geometric model of the quality of the studied glycerin-containing control sample from technical animal fats based on a two-sided evaluation (Figure 3).

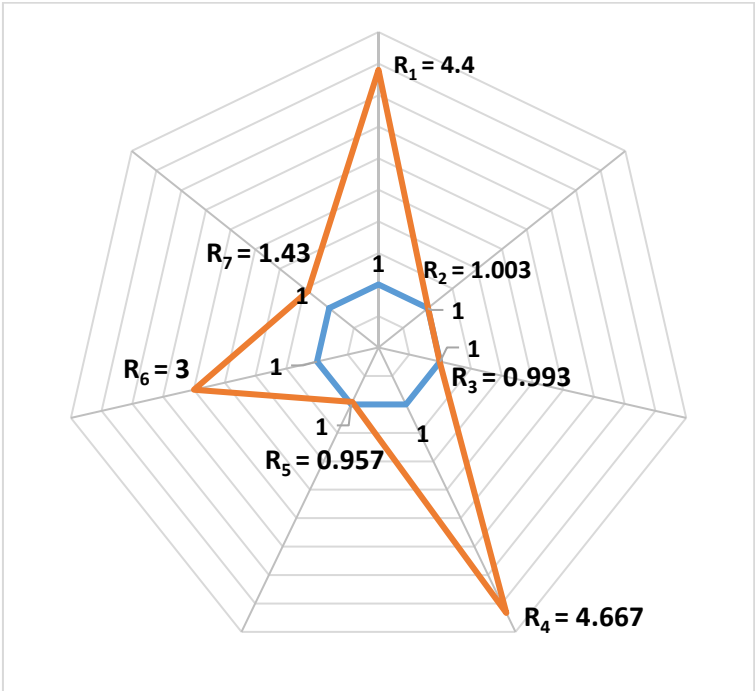


Figure 3 Mathematical model of the quality of the studied sample of glycerin-containing products from *technical animal fats* according to the main characteristics of products during bilateral evaluation using the standard D – 98.

The analysis of geometric models in Figure 3 shows that the sample of glycerin-containing products from technical animal fats significantly exceeds the regulatory values for color number, glycerin reaction, and ash content, namely, by 4.4, 4.66, and 3 times, respectively.

In general, across the studied main product characteristics, the norm is exceeded by 3.58 times (Table 2). Using the calculated values of the current parameters R_i, a geometric model of the quality of the studied glycerin control sample from waste oils was built using a two-sided evaluation (Figure 4).

Using the calculated values of the current parameters R_i, a geometric model of the quality of the studied glycerin control sample from rapeseed oil was built using a two-sided evaluation (Figure 5).

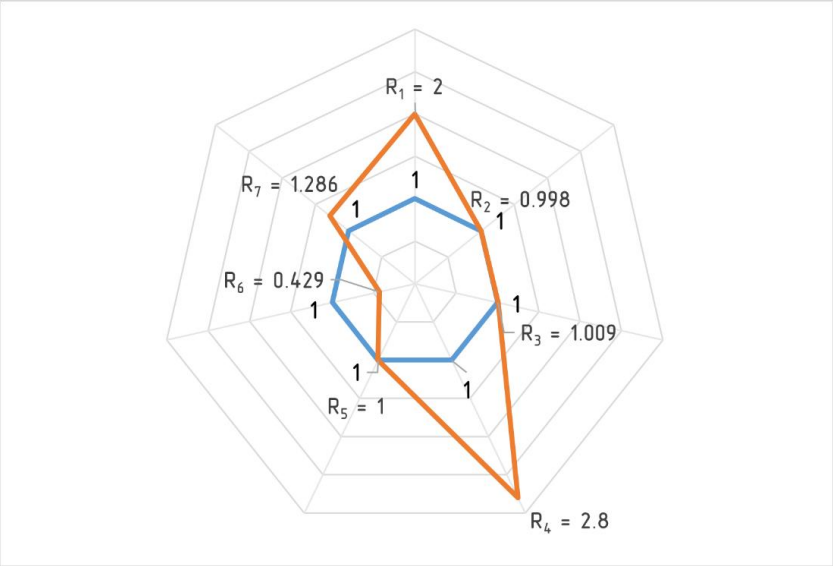


Figure 4 Mathematical model of the quality of the studied sample of glycerin from waste oils according to the main characteristics of the product during two-sided evaluation using the D – 98 standard.

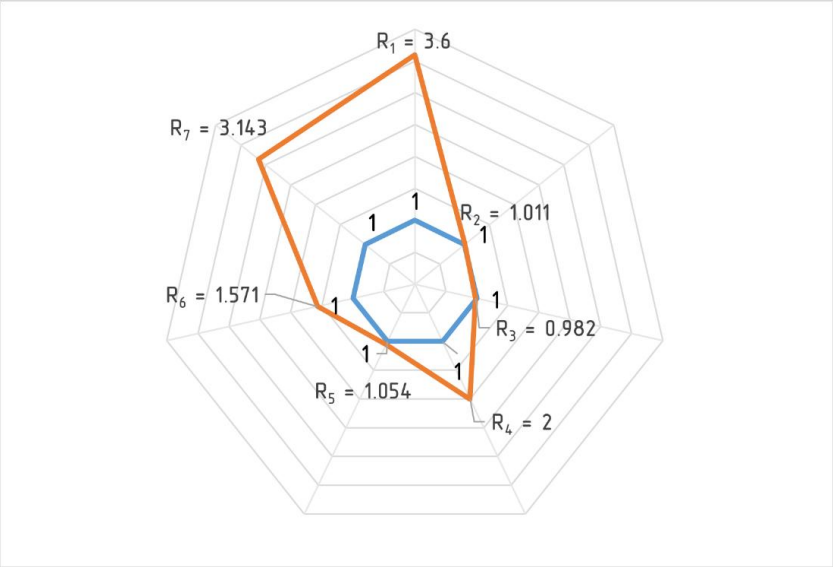


Figure 5 Mathematical model of the quality of the studied sample of glycerin from rapeseed oil according to the main product characteristics during two-sided evaluation using the D – 98 standard.

Analysis of the geometric models in Figure 4 shows that the glycerin sample from waste oils exceeds the standard values for color number and glycerin reaction by 2.0 and 2.8 times, respectively; for the saponification coefficient, the excess over the average standard value is 28.6%. The remaining estimated indicators are included in the standard indicators; therefore, across all the studied main characteristics of the product, the standard is slightly exceeded by 1.68 times. Based on experimental data for glycerin from rapeseed oil, the main quality parameters were calculated to build a mathematical model using 7 key characteristics of the studied product sample.

Analysis of geometric models in Figure 5 shows that the sample of glycerin from rapeseed oil significantly exceeds the normative values for color number and saponification coefficient by 3.6 and 3.143 times, respectively; for the reaction of glycerin, the average normative value is exceeded by 2 times, and for the mass fraction of ash, by 1.571 times. The remaining estimated indicators are included in the normative indicators. For the integral quality indicator, which takes into account the calculated data for all the product's main characteristics, the norm is exceeded by 3.56 times.

Based on experimental data for glycerin from sunflower oil, the main quality parameters for building a mathematical model were calculated (Table 1) using 7 main characteristics of the studied product sample. Using the calculated values of the current parameters Ri, a geometric quality model of the studied glycerin sample from sunflower oil was built using a two-sided evaluation (Figure 6).

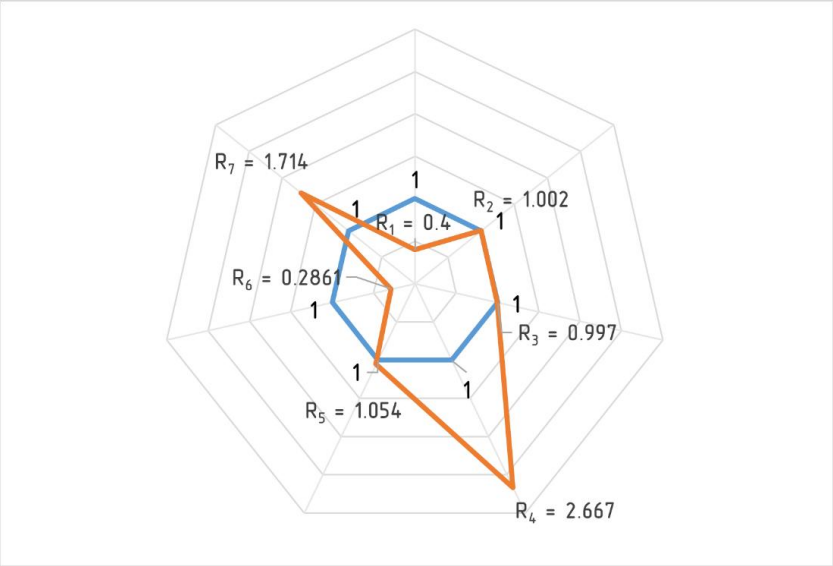


Figure 6 Mathematical model of the quality of the studied sample of glycerin from sunflower oil according to the main characteristics of the product during two-sided evaluation using the D – 98 standard.

Analysis of the geometric models in Figure 6 shows that the sample of glycerin from sunflower oil slightly exceeds the normative values for the glycerin reaction and saponification coefficient, respectively, by 2.667 and 1.714 times. The remaining estimated indicators are included in the normative indicators, resulting in the integral quality indicator exceeding the norm by only 14%.

Based on experimental data for glycerin from soybean oil, the main quality parameters were calculated to build a mathematical model (Table 1) using 7 key characteristics of the studied product. Using the developed calculation method, the current parameter values Ri were determined, and a geometric model of the quality of the studied soybean oil-derived glycerin was constructed using a two-sided evaluation (Figure 7).

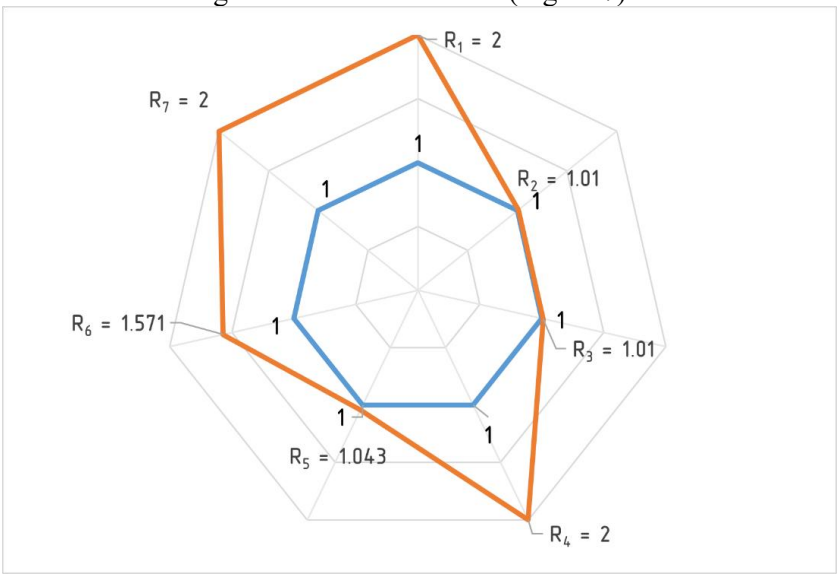


Figure 7 Mathematical model of the quality of the studied sample of glycerin from soybean oil according to the main characteristics of the product during two-sided evaluation using the D – 98 standard.

Analysis of geometric models in Figure 7 shows that the sample of glycerin from soybean oil exceeds the standard values by 2 times for color number, glycerin reaction, and saponification coefficient; by mass fraction of ash by 1.57 times. The remaining estimated indicators are included in the standard indicators, resulting in the integral quality indicator exceeding the standard by 24%.

Based on the results of mathematical modeling using the factor space method, the criteria for assessing the quality of the studied glycerin-containing products are presented in Table 3.

Table 3 Criteria for assessing the quality of the studied samples of glycerin.

№ п/п	Product type	Factor area		Evaluation criteria	
		S_H, con. un^2	S_N (S_c), con. un^2	k_{VQ}	k_{VN}
Assessment using the D-98 standard					
1	Glycerin from technical animal fats	9.79	2,736	3.58	1,376
2	Glycerin from used oils	4.58	2,736	1.68	0,885
3	Glycerin from rapeseed oil	9.73	2,736	3.56	1,162
4	Glycerin from sunflower oil	3.11	2,736	1.14	0,785
5	Glycerin from soybean oil	3.39	2,736	1.24	0,968

Note: The table presents the following evaluation characteristics: S_i is the factor area of current parameters, which was determined by a two-sided assessment; S_c is the average standard factor area, which was determined by a two-sided assessment; k_{VQ} is the coefficient of compliance with the maximum quality standards; k_{VN} is the coefficient of compliance with a given quality interval.

Based on the data in Table 3, a comparative graph-analytical analysis of changes in the criteria for assessing the quality of the studied glycerin-containing products was conducted using the D-98 standards (Figure 8).

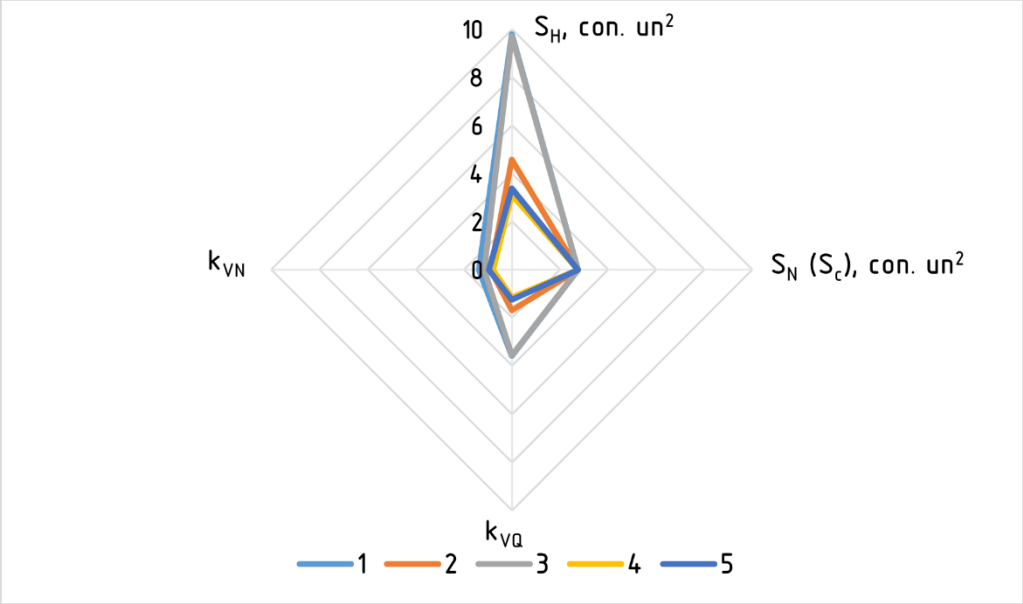


Figure 6 Comparative analysis of changes in the criteria for assessing the quality of the studied glycerin samples using the D – 98 standard: 1 – glycerin from technical animal fats, 2 – glycerin from used oils, 3 – glycerin from rapeseed oil, 4 – glycerin from sunflower oil, 5 – glycerin from soybean oil.

The assessment according to the D-98 standard (Figure 8) revealed that the factor space for glycerin samples from technical animal fats and rapeseed oil exceeds the standard indicators by more than 3.5 times, while the remaining indicators exceed the standard by 25–70%. Exceeding the maximum permissible norms by 1.2–1.4 times was observed in glycerin samples from technical animal fats and rapeseed oil (Table 3). The best-quality characteristics are observed in glycerin samples from soybean oil and waste oils (Figure 8).

The results obtained in this study support the initial objective of developing a multifactor approach for the integrated assessment of glycerin-containing products derived from fatty and oily raw materials. The working hypothesis was that a polygonal modeling framework combining multiple physicochemical indicators would enable a more informative evaluation of product quality than single-parameter analysis. The findings generally confirm this assumption, as the model revealed clear differentiation among samples depending on raw material origin and parameter interactions. From an experimental perspective, the intervention consisted of a sequence of post-transesterification treatment stages (neutralization, removal of volatile components, and filtration) applied at the batch level to glycerin-containing products. The allocation of treatment was therefore uniform within each batch, while comparisons were conducted at the sample level across different feedstock origins. The timing of interventions corresponded to the final stage of the production process, ensuring that the measured parameters reflect the resulting product state rather than intermediate transformations.

The analysis demonstrated that samples from technical animal fats and rapeseed oil exhibited significant deviations in several physicochemical indicators, resulting in pronounced deformation and enlargement of the

polygonal model areas. In contrast, samples derived from sunflower and soybean oil showed more balanced parameter distributions and relatively stable geometric configurations. These findings indicate that the interaction among multiple quality indicators plays a decisive role in determining overall product suitability, consistent with the concept of multicomponent system evaluation **[27]**, **[28]**, **[29]**.

However, the interpretation of these results must remain cautious. Although integrated indicators suggest improved quality profiles for certain samples, individual parameters in some cases approach or exceed recommended limits, which prevents definitive conclusions regarding regulatory compliance. This observation highlights a key limitation of integral modeling approaches, where aggregation may obscure parameter-specific deviations **[30]**, and **[31]**.

Potential sources of bias should also be considered. First, selection bias may arise from the limited number and diversity of sample types, which can reduce the dataset's representativeness and influence the observed relationships **[32]**. Second, measurement bias can arise from the inherent limitations of analytical methods, particularly for low-concentration impurities, leading to underestimation and affecting model inputs **[33]**. Third, model-based bias may result from the assumption of equal or predefined parameter importance within the polygonal framework, potentially amplifying the influence of extreme values **[34]**.

Imprecision in the results may also be associated with experimental variability at the batch level and the absence of repeated large-scale trials. While laboratory conditions ensured controlled measurements, they do not fully reproduce the variability typical of industrial processing systems, including fluctuations in raw material composition and processing conditions **[35]**. Consequently, the bias is likely toward overestimating model stability and reproducibility, while the magnitude remains difficult to quantify without additional validation datasets.

The diversity of analyses in this study is reflected in the combination of physicochemical characterization and geometric modeling. This approach allows not only the assessment of individual indicators but also the identification of their interactions, which are manifested as changes in polygon shape and area. Such multidimensional representation aligns with recent trends in quality assessment of complex systems, where integrated metrics are increasingly used to improve classification and decision-making accuracy **[36]**, **[37]**, **[38]**.

The obtained results are generally consistent with previous studies demonstrating that the quality of crude glycerin is determined by a combination of impurities and physicochemical properties rather than isolated parameters **[39]**, **[40]**. Several authors have emphasized that achieving high product quality requires simultaneous control of multiple variables, particularly in systems derived from heterogeneous feedstocks **[41]**, and **[42]**. Furthermore, recent advances in mathematical modeling highlight the advantages of integral and hybrid approaches for evaluating multicomponent systems **[43]**, **[44]**, **[45]**.

The results obtained are in good agreement with modern scientific data, which indicate that crude glycerin contains high levels of water, methanol, soaps, mineral impurities, and other organic components, thereby limiting its scope of application. In particular, the work of Maquirriain et al. **[46]** shows that impurity composition determines the complexity and multi-stage nature of purification processes and accounts for the main production costs.

Similar conclusions are reported in the study by Dhabhai et al. **[47]**, which shows that achieving a purity of more than 90% yields a product with properties close to those of commercial glycerin, underscoring the importance of controlling physicochemical parameters. A comparative analysis of the results obtained shows that the patterns established in the work are consistent with modern approaches to mathematical modeling of the quality of multicomponent systems. In particular, the studies of Chuaypat et al. **[48]** and Silva et al. **[49]** show that increasing the accuracy of assessing glycerin quality is achieved by using integral indicators that account for the set of physicochemical parameters, rather than their individual values.

The results also confirm the conclusions of Rathee et al. **[50]** regarding the decisive role of a multifactorial approach in quality assessment tasks, when the integral indicator is formed by the synergistic interaction of parameters. In the framework of this study, this is manifested in a change in the shape and area of the polygon as a generalized quality criterion, which allows not only quantitative assessment of the sample's state but also the identification of the dominant influencing factors.

Similarly, in the work of Aslan **[51]**, the effectiveness of using mathematical models to integrate heterogeneous indicators into a single assessment system is emphasized. In our case, the polygonal model serves as a visualization and analytical interpretation tool, enabling us to compare samples according to a set of criteria. This is a significant advantage over classical regression models, which often lack a visual representation of multidimensional dependencies.

Modern studies also confirm the feasibility of using models that adapt to different quality assessment scenarios. In particular, Maya-Rodriguez et al. **[52]** note the importance of flexible modeling approaches that allow for the specificities of the product's final use. In the proposed polygonal model, this is implemented by allowing the

weight coefficients of individual indicators to vary, thereby enabling the model to adapt to different assessment conditions. Additionally, it was found that the use of polygonal models allows identifying not only the absolute values of the indicators, but also their imbalance, which manifests as deformation of the polygon's geometric shape. This opens the possibility of a more in-depth analysis of the qualitative state of glycerin, compared to traditional approaches based on the limit values of individual parameters.

Thus, the conducted comparative analysis confirms that the use of mathematical polygonal models is an effective tool for assessing the quality of glycerin. This approach ensures the integration of multifactorial data, enhances the informativeness of the analysis, and aligns with modern trends in the development of mathematical modeling methods for assessing the quality of multicomponent systems.

Limitations

This study has several limitations that should be considered when interpreting the results.

First, the number and diversity of sample types were limited, limiting the dataset's representativeness and potentially affecting the generalizability of the findings across a broader range of glycerin-containing products and feedstocks. This limitation is particularly relevant given the variability in raw material composition and processing conditions in industrial practice.

Second, the proposed mathematical model was not externally validated using independent datasets. Therefore, its predictive performance and robustness remain uncertain beyond the specific experimental conditions considered in this study. External validation is required to confirm the model's reliability and transferability.

Third, the experimental work was conducted under controlled laboratory conditions, which do not fully replicate the complexity and variability of real industrial glycerin processing systems. As a result, scale-dependent effects and process fluctuations may not be adequately captured.

Fourth, the polygonal modeling approach is based on a selected set of physicochemical indicators and implicitly assumes their relative importance, without using formally derived weighting coefficients. This may introduce bias in the integral quality assessment and influence the ranking of samples.

Finally, the analytical methods employed have inherent sensitivity and detection limits, which may lead to underestimation of low-concentration impurities and affect the accuracy of certain parameters.

Taken together, these limitations indicate that the results should be interpreted with caution. Further research should focus on expanding the dataset to include a broader range of raw materials, validating the model externally, and testing the approach under industrial or pilot-scale conditions.

CONCLUSION

The study demonstrates the applicability of a mathematical modeling approach for the integrated assessment of the quality of glycerin-containing products derived from fatty and oily raw materials. The proposed framework, based on a set of physicochemical indicators (color number, relative density, density at 20 °C, alkaline glycerin reaction, mass fractions of pure glycerin and ash, and saponification coefficient), provides a structured basis for multidimensional analysis and comparative evaluation. The use of polygonal models enabled a generalized quantitative characterization of sample quality and revealed clear differentiation between raw material types. In particular, samples from technical animal fats and rapeseed oil exhibited substantial deviations across several parameters, in some cases exceeding regulatory or recommended values by more than 3.5 times, indicating limited suitability without additional processing or refinement. For samples derived from sunflower and soybean oils, the modeling results suggest more favorable quality profiles and greater stability across the evaluated indicators. However, it should be noted that some individual parameters (e.g., glycerin reaction, saponification coefficient, color number, and ash content) approached or exceeded recommended limits. Therefore, full compliance with regulatory requirements cannot be conclusively confirmed and should be verified through parameter-specific validation. The analysis of polygonal model factor areas further supported these trends, showing a pronounced increase for samples from technical fats and rapeseed oil, while samples from vegetable oils generally demonstrated more moderate variations. At the same time, the observed differences should be interpreted with caution, as the integral model may amplify the influence of individual outlying parameters. Overall, the proposed modeling approach can be considered a promising tool for preliminary screening, comparative ranking, and identification of quality deviations in glycerin-containing products. Nevertheless, its use as a standalone method for regulatory compliance assessment remains limited and requires additional validation. Future research should focus on improving the model's robustness by incorporating parameter weighting coefficients, expanding the experimental dataset, and integrating machine learning techniques to enhance predictive accuracy and reliability.

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