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DETERMINING THE OPTIMAL COMPOSITION OF STABILIZATION SYSTEMS IN STRUCTURED LOW-CALORIE DAIRY DESSERTS WITH PROTEIN AND CARBOHYDROGEN COMPONENTS

This study investigates structured low-calorie dairy desserts with multi-component stabilization systems, including protein and carbohydrate components.

The issue of the ratio of stabilization systems' components and their influence on the structural-mechanical and organoleptic characteristics of the product remains insufficiently studied. The lack of substantiated mathematical models complicates the targeted design of recipes with predefined properties.

Mathematical models of the dependence of viscosity on the ratio of components in the stabilization system have been constructed. For puddings with the "gelatin-starch-rice flour" system, the effective viscosity based on buttermilk was 12717–14381 mPa·s, based on retentate – 18220–25864 mPa·s. For creams with the "pectin-inulin-whey" system – 3640–5063 mPa·s and 4097–5836 mPa·s, respectively.

Organoleptic and physicochemical indicators confirmed that the optimized stabilization systems provide a stable structure of desserts with proper organoleptic characteristics and high moisture retention capacity.

It was established that the interaction of protein molecules with polysaccharide chains during thermomechanical processing leads to the formation of a stable gel structure and an increase in water-binding capacity. Taking these interactions into account in mathematical models has made it possible to determine the optimal composition of stabilization systems.

The effectiveness of combining rice flour, starch, and gelatin for structuring pudding; inulin, pectin, and demineralized whey for cream was confirmed by mathematical modeling.

The results could be used by dairy processing enterprises when devising low-calorie products with a predefined structure

Keywords: dairy desserts, low-calories, stabilization systems, pudding, cream, composition design, viscosity

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1. Introduction

In modern nutrition, especially under conditions of a sedentary lifestyle and low costs, the greatest attention in the structure of nutrition should be paid to the ratio between animal and plant products. Important characteristics of nutrition are the nutritional and biological value of food, macro- and microelement composition, and safety [1, 2]. Proper nutrition organization involves the intake of not only a sufficient amount of nutrients into the human body but also their strictly defined qualitative composition, which corresponds to the adaptive capabilities of the gastrointestinal tract and the level of its metabolic processes. To ensure rationally balanced nutrition of people, the diet should include all the basic nutrients in the required quantities and ratios: proteins, fats, carbohydrates, vitamins, minerals, etc. [3, 4].

Devising new types of food products consists of two related processes – design and construction. In accordance with modern ideas, the concept of "design" means the construction of models that regulate all stages in making products of predefined quality. Models are a system of equations that reflect all changes in one or more key parameters on the basis of which they are devised. The presence of the aforementioned system of equations allows one to describe quite correctly changes in the general chemical, amino acid, fatty acid, and other components of the compositions being developed, depending on the ratio and quota of raw materials. This makes it possible to replace further studies on the process of forming the product composition with the analysis of its mathematical model to obtain a solution to the specific tasks set [5]. With the help of systems of equations, it is possible to design and construct food products that are not only safe for humans but also protect against the negative effects of the external environment using functional products [6].

At the same time, there is also a lack of research on the coordination of structural changes during the technological process with the desired sensory and rheological properties of the finished product. This uncertainty primarily concerns the mechanisms of interaction between protein and carbohydrate components as a result of various types of processing, in particular thermomechanical [7]. There are also no unified approaches to modeling the composition of multicomponent stabilization systems in dairy products.

Conventional empirical optimization methods are insufficient for predicting multicomponent dairy desserts with protein and carbohydrate components. Mathematical modeling of the composition of stabilization systems allows one to overcome these limitations and ensure the formation of the structure of desserts with specified characteristics. This creates a basis for devising recipes for structured low-calorie dairy desserts with a stable structure, optimal consistency, and high nutritional value.

Therefore, research aimed at determining the optimal composition of stabilization systems for structured low-calorie dairy desserts with protein and carbohydrate components based on secondary dairy raw materials is relevant.

2. Literature review and problem statement

Dairy producers are increasingly focusing on the use of affordable and inexpensive raw materials that are characterized by increased nutritional and biological value, in particular, the balance of proteins in terms of amino acid composition. In this case, the most appropriate, from the point of view of application technology, are secondary dairy products, in particular protein products of membrane filtration (dry whey and milk protein concentrates, demineralized whey powder, retentate, etc.), buttermilk, skimmed milk, etc. Protein concentrates are capable of foaming and gelation, which expands the possibilities of their use for the production of products with a foam-like structure [8]. They can completely or partially replace egg yolk, hydrocolloids, soy protein, or modified starch. The most important functions of whey protein concentrates in low-fat products are binding with water, emulsification, high solubility, gelation, increasing viscosity, and enhancing adhesive interactions [9]. Dry dairy products are convenient to transport, have a long shelf life, do not require special storage conditions, are easy to dose, and have constant quality indicators (physicochemical, organoleptic, microbiological) [9].

However, both cited papers are limited to a general characteristic of the functional properties of protein concentrates and do not consider their behavior in systems with a reduced fat content based on buttermilk and retentate. The interaction of whey protein concentrates with polysaccharides in the composition of structured low-calorie dairy desserts is also not studied. At the same time, the optimal content of these components for the formation of the predicted structural and mechanical characteristics of dessert products has not been established.

Buttermilk proteins contain almost all fractions of whole milk proteins and have an identical set of amino acids, including essential ones, including antioxidant amino acids (methionine + cystine). The biological properties of these amino acids are especially effectively manifested in combination with vitamins B_1, B_2, B_{12}, C, E and pantothenic acid, which are part of buttermilk [10]. However, the cited study does not provide information on the technological properties of buttermilk as a raw material for structured low-calorie dairy desserts. In particular, its gelling ability, behavior during thermomechanical processing and interaction with components of the stabilization system, which makes it impossible to directly use these data when developing the composition of dairy desserts.

During the concentration process by nanofiltration, whey is divided into retentate and permeate. The retentate has all the parameters of whey but is concentrated almost 3.5 times. One of the most valuable components of the retentate is whey proteins. The biological value of proteins is determined by the optimal set of essential amino acids. From the point of view of nutritional physiology, the ratio of the set of amino acids whey proteins have the highest coefficient of biological value among food proteins and approach the amino acid scale of the "ideal" protein, in which the ratio of amino acids corresponds to human needs. The low glycemic index of whey proteins makes it possible to optimize insulin secretion, regulating blood glucose levels and, thereby, preventing the occurrence of type 2 diabetes [11]. Despite the detailed coverage of the nutritional value of whey proteins, no data are provided on the effect of retentate on the structure formation and quality of low-calorie dairy desserts.

The chemical composition of buttermilk and retentate is complete due to the presence of all protein compounds of milk, the preservation of carbohydrate and mineral complexes, enriched lipid fractions due to phospholipids, volatile fatty acids, polyunsaturated fatty acids. Buttermilk and retentate have high biological value and are a source of food nutrients, which makes them suitable for use as a basis for the production of dairy products for dessert purposes.

The authors of [12] substantiated the relevance of making functional dairy products with reduced sugar content. It was noted that excessive sugar consumption causes obesity, diabetes, and cardiovascular diseases. At the same time, sugar significantly affects the texture, viscosity, and color of products, so its replacement requires careful selection of functional ingredients. However, specific data on the composition of stabilization systems capable of reproducing the structure-forming functions of sugar in desserts based on secondary dairy raw materials are not provided. It remains unclear how changing sugar content affects the interaction between the components of the recipe and the structural and mechanical indicators of the finished product.

One of the most widely used prebiotics in dairy products is long-chain inulin. In [13] it was shown that adding inulin to the milk mixture changes the structural and mechanical characteristics of the finished products. At the same time, the optimal amount of inulin has not been determined and its interaction with such structure-forming agents as gelatin, starch, rice flour, pectin, in the composition of dairy desserts based on buttermilk and retentate has not been studied.

The composition of stabilization systems for dairy desserts (cream and pudding) has been substantiated, taking into account the functional properties of gelatin, starch, whey protein concentrate, rice flour, and inulin. The devised desserts were characterized by high organoleptic and structural-mechanical indicators [14]. However, the optimization of the composition of the stabilization system of dairy desserts by the method of a full factorial experiment has not been carried out.

In study [15], the effect of a protein-polysaccharide complex (sodium caseinate-carboxymethylcellulose-locust bean gum) on the physical and textural characteristics of low-fat whipped cream was analyzed. The ratio of components was optimized using the response surface method. It was found that the proposed combination of stabilizers increases the effective viscosity and improves the organoleptic characteristics of the product. The optimal content was 0.35% sodium caseinate, 0.15% carboxymethylcellulose, and 0.15% locust bean gum. In [15], the use of secondary dairy raw materials was not considered, and the established concentrations of stabilizers require additional study for use in structured low-calorie dairy desserts.

The rheological properties of lactose-free dairy desserts with different types of gums and waxy corn starch were investigated. It was found that κ-carrageenan is the most effective gum for providing a stable structure of dairy desserts [16]. However, the study was conducted on lactose-free systems that differ in the nature of protein-polysaccharide interactions from dairy desserts based on buttermilk and retentate.

In paper [17], the experimental design method was used to optimize the composition of a dairy dessert using white lupin and stevia extract. Eighteen tests of dairy desserts were conducted, which included different concentrations of lupin milk. Reducing the amount of sucrose and using stevia rebaudiana extract led to the dairy dessert containing less sugar. As a result, an optimal formula with good sensory characteristics was devised. The experimental methodology used in [17] is a valuable methodological basis; however, the composition of lupin milk is fundamentally different from that of buttermilk and retentate both in composition and in the mechanisms of structure formation.

In study [18], the composition of a milk-based fruit cream was optimized using response surface methodology to achieve the desired sensory characteristics. Using the 3-factor version of Central Composite Rotatable Design version 8.02 (Stat-Ease, Inc., USA), a recipe of 80 g of cream, 80 g of fruit mixture, and 19.89 g of sugar was selected for the production of fruit cream. The selection criteria were the evaluation of the color, appearance, consistency, aroma, taste, and overall acceptability of the product. The methodology used in [18] can serve as an analytical guideline; however, the object of the study, fruit cream, differs significantly from structured low-calorie dairy desserts based on buttermilk and retentate in terms of composition and gelation mechanisms. The optimization results cannot be directly applied to dairy desserts without appropriate readjustment.

In [19], a comprehensive approach to the design of dairy products is proposed, which includes the analysis of the relationships between the composition, technological process, and structural properties. It is established that the design of a food product is a multifactorial task. It is proven that a comprehensive approach to the design of the composition of food products enables the purposeful formation of the quality of functional dairy products through the coordination of the component composition, technological process, and target characteristics of the finished product. The comprehensive approach to the design of dairy products proposed in [19] has conceptual value but remains mainly theoretical. The study does not contain specific quantitative data on the optimal ratio of components for structured low-calorie dairy desserts based on secondary dairy raw materials. Moreover, the role of the composition of the stabilization system in the formation of the structural properties of such products is not considered.

Although the issue of designing the composition of dairy products has been partially investigated, the influence of multicomponent formulations on the structural characteristics of desserts has not been studied sufficiently. The results of study [20] confirm the key role of optimizing the component composition in the formation of the structural and mechanical properties of dairy products. However, comprehensive studies for dairy desserts based on secondary raw materials in this direction are lacking. In particular, the issues of optimizing the composition of the formula for dairy desserts based on buttermilk and retentate remain open, and there is no data on the influence of protein and carbohydrate components on the quality indicators of structured deserts and the nature of their interaction.

To overcome these difficulties, the use of a multiscale approach to the design of food systems [21] is promising, which makes it possible to establish the relationship between the composition and quality indicators. However, detailed data on the influence of the optimized composition of the stabilization system based on protein and carbohydrate components on the structural and mechanical properties of dairy desserts based on secondary raw materials have not yet been obtained. This confirms the feasibility of a study aimed at determining the optimal composition of multicomponent stabilization systems for structured low-calorie dairy desserts based on buttermilk and retentate.

3. The aim and objectives of the study

The aim of our study is to determine the optimal composition of multicomponent stabilization systems for structured low-calorie dairy desserts with protein and carbohydrate components. This will make it possible to obtain structured low-calorie dairy desserts with stable organoleptic, physicochemical, and rheological indicators.

To achieve the goal, the following tasks were set:

– to build mathematical models for optimizing the composition of multicomponent stabilization systems for obtaining low-calorie structured dairy desserts;

– to determine the influence of protein and carbohydrate components in the composition of the optimized stabilization system on the structural-mechanical, organoleptic, and physicochemical indicators of structured low-calorie dairy desserts.

4. The study materials and methods

The object of our study is structured low-calorie dairy desserts with multi-component stabilization systems, including protein and carbohydrate components.

The subject of the research was secondary dairy raw materials – buttermilk and retentate; the finished product – structured low-calorie dairy dessert. Components for the stabilization system – dry whey protein concentrate (WPC), dry demineralized whey (DDW), rice flour, highly methoxylated pectin, inulin, corn starch, gelatin.

The principal hypothesis assumes that the analysis of intercomponent interactions in structured low-calorie dairy desserts in combination with mathematical modeling methods makes it possible to design the composition of stabilization systems for different types of structures. It is expected that optimization of protein and carbohydrate ingredients of stabilization systems would ensure the formation of a stable structure of structured low-calorie dairy desserts with predicted rheological and physicochemical characteristics, as well as high organoleptic indicators while simultaneously reducing calorie content.

When planning and conducting research, the following assumptions were adopted:

– the use of secondary dairy raw materials (buttermilk and retentate) is considered a priority due to their high biological value and the presence of complexes of full-fledged proteins;

– it is assumed that the structure formation of low-calorie dairy desserts during thermomechanical processing depends mainly on the interaction of selected protein and carbohydrate components (WPC, DDW, rice flour, starch, gelatin, inulin, pectin) with the milk base;

– the conditions of thermomechanical processing of milk mixtures at a temperature of 80–85°C with a holding time of 90 s are accepted as optimal for the manifestation of the functional properties of all components of the milk mixture;

– it is believed that the effective viscosity indicators are the main criterion for the quality of the formed structure of low-calorie dairy desserts and its stability in general.

To ensure the adequacy of mathematical modeling, the following simplifications were accepted:

– during the modeling, the influence of only the dominant components of the stabilization system was taken into account, in particular, starch and gelatin for puddings or inulin and pectin for creams, without taking into account the composition of the main dairy raw materials;

– the evaluation of physicochemical and organoleptic indicators was carried out according to such characteristics of the finished product as moisture retention capacity, consistency, color, and taste, which corresponds to the generally accepted methodology for assessing the quality of food products of this type.

Thermomechanical processing of milk mixtures with carbohydrate and protein components was carried out in a rotary-vortex emulsifier Ya5-OEV (Institute of Food Resources of the National Academy of Sciences of Ukraine, Ukraine) at a rotor speed of 2800 rpm, the temperature and duration of processing were 80–85°C and 90 seconds, respectively.

The effective viscosity was determined on a rotational viscometer ATAGO-895 VISCO (Japan) using S/S_2 measuring cylinder devices and viscosity indicators were recorded from an electronic display. The S_2 measuring cylinder (rotor) was selected so that the gradient layer extended over the entire thickness of the product layer placed in the annular gap of the viscometer measuring device. For each experiment, a new portion of the product was taken and, after reaching the specified temperature, it was thermostated for 20 minutes.

Titrated acidity was determined according to DSTU ISO 11869:2007; active acidity – according to DSTU 8550:2015; dry matter content – according to DSTU ISO 6731:2007; protein content – according to DSTU ISO 8968-1:2005 (Kjeldahl method); fat content – according to DSTU ISO 2446:2019 (Gerber method); ash content – by the method of burning a sample in a muffle furnace at a temperature of (400–500) °C; carbohydrate content – by the calculation method as the difference between the mass fraction of dry matter and the sum of the mass fractions of fat, protein and ash; energy value – by the calculation method in accordance with EU Regulation 1169/2011.

Moisture retention capacity (%) was determined by centrifugation (4000 rpm, 5 min) as the ratio of the volume of retained moisture to the total volume of the sample, multiplied by 100.

To compare the organoleptic indicators of cream and pudding, a quantitative descriptive (profile) test was used in accordance with ISO 13299:2016, which makes it possible to compare taste characteristics visually.

Before conducting the tests, based on literature data, a list of parameters was selected that play an important role in assessing the quality of dairy desserts: color, taste, smell, consistency, aftertaste. Each of the listed indicators was evaluated based on a maximum score of 5 points [22]. The characteristics of the descriptors are given in Table 1.

To optimize the composition of the stabilization system within the two-factor model, the viscosity dependence modeling methodology (VIS) was used on the content of components in the stabilization system. In the case of pudding production, on the content of starch and gelatin in the stabilization system; in the case of cream production, on inulin and pectin.

Experiments were set up according to the full-factorial experiment (FFE) plan 2^3. Each experiment was repeated three times.

The following factors were selected as those that affect the viscosity of the pudding:

– z_1 – amount of gelatin (%):

– z_2 – amount of starch (%):

– z_3 – amount of rice flour (%):

The following factors were selected as influencing the viscosity of the cream:

– z_1 – amount of inulin (%):

– z_2 – amount of pectin (%):

– z_3 – amount of demineralized dry whey (%):

Number of experiments: $N = 2^3 = 8$ $N = 2^3 = 8$; number of trials in the experiment: $m = 3$.

Table 2 gives the initial planning matrix FFE 2^3 for pudding and cream stabilization systems.

For each factor, we find the center, variation interval, and dependence of the coded variable x_i on natural variable z_i for pudding (Table 3) and for cream (Table 4).

Table 1

Organoleptic characteristics of structured low-calorie dairy desserts

Descriptor	Descriptor characteristics	Characteristics of defects	Points discount	Quality score level
Color	Homogeneous, uniform throughout the mass, milky-creamy, characteristic of a certain type of dessert (added filler)	No defects	0	5
		Uneven color	1	4
		Uneven color, excessive or not pronounced	2	3
		Not suitable for a certain type of dessert	3	2
		Strong foreign color, presence of mold on the surface	4	1
Taste	Clean, milky, characteristic of a certain type of dessert, a slight taste of pasteurization is acceptable	No defects	0	5
		Pronounced pasteurization flavor	1	4
		Pronounced taste of one of the components of the mixture	2	3
		Unclean, uncharacteristic for a certain type of dessert	3	2
		A sharp foreign taste	4	1
Smell	Clean, milky, typical for a certain type of dessert	Without defects	0	5
		Unclean	1	4
		Uncharacteristic for a certain type of dessert	2	3
		Ranked	3	2
		Harsh foreign taste	4	1
Consistency	Homogeneous throughout the mass, moderately dense, without the presence of lumps of protein and brewed starch	No defects	0	5
		Heavy structure, noticeable lumps of components	1	4
		Foamy consistency, excessively dense	2	3
		Loose, floury,	3	2
		Liquid, viscous, watery	4	1
Flavor	Pleasant milky flavor characteristic of a certain type of dessert	Without defects	0	5
		Excessively pronounced	1	4
		Excessively sweet	2	3
		Excessively salty or other foreign taste	3	2
		Impurity, putrid	4	1

Table 2

Initial planning matrix FFE 2^3 for the stabilization system of structured low-calorie dairy desserts

Experiment No.	Factors under study			VIS of pudding, mPa*c per 1 s^{-1}			VIS of cream, mPa*c per 1 s^{-1}		
	z_1	z_2	z_3	y_1	y_2	y_3	y_1	y_2	y_3
1	+	+	+	14,420.2	14,481.2	14,512.4	3,740.3	3,795.5	4,684.1
2	–	+	+	13,706.5	13,768.7	13,795.3	4,063.5	4,173.1	4,352.7
3	+	–	+	14,223.7	14,125.9	14,201.5	3,941.2	3,963.5	3,951.6
4	–	–	+	12,758.5	12,875.5	12,789.4	3,963.5	4,078.6	3,997.3
5	+	+	–	14,021.7	14,059.5	14,160.3	3,700.5	3,704.4	3,702.4
6	–	+	–	13,778.5	13,720.5	13,629.6	4,280.4	4,852.7	4,589.7
7	+	–	–	14,089.1	14,028.3	14,146.2	4,725.6	4,685.9	4,703.1
8	–	–	–	12,536.3	12,583.6	12,665.4	4,790.9	4,966.7	4,580.7

Table 3

Coding factors for pudding

Factor	Upper level z_i^+	Lower level z_i^-	Center z_i^0	Interval of variation λ_i	Dependence of the encoded variable on the natural variable
z_1	1.5	0.5	1.0	0.5	$x_1 = \frac{z_1 - 1.0}{0.5}$
z_2	1.5	0.5	1.0	0.5	$x_2 = \frac{z_2 - 1.0}{0.5}$
z_3	2.0	1.0	1.5	0.5	$x_3 = \frac{z_3 - 1.5}{0.5}$

All studies were performed five times in three identical samples of dairy desserts. Tukey-Kramer multiple comparison was used to compare mean values, considering that significant differences were observed at $p < 0.05$. Experimental data were processed by methods of mathematical statistics using Microsoft Excel (Microsoft 365 package, USA; licensed to Ivan Pulyuy Ternopil National Technical University).

Table 4

Coding factors for cream

Factor	Upper level z_i^+	Lower level z_i^-	Center z_i^0	Interval of variation λ_i	Dependence of the encoded variable on the natural variable
z_1	1.5	0.5	1.0	0.5	$x_1=\frac{z_1-1.0}{0.5}$
z_2	1.5	0.5	1.0	0.5	$x_2=\frac{z_2-1.0}{0.5}$
z_3	4.0	2.0	1.5	0.5	$x_3=\frac{z_3-1.5}{0.5}$

5. Results of the study on determining the optimal composition of stabilization systems for structured low-calorie dairy desserts

5. 1. Mathematical modeling of the composition of stabilization systems for structured low-calorie dairy desserts

In order to determine the optimal ratio of protein and carbohydrate components of the stabilization system for structured low-calorie dairy desserts, planning matrices were compiled taking into account all interactions and average response values for pudding and cream (Tables 5, 6).

The calculated coefficients of the regression equation are given in Table 7.

Table 5

Planning matrix for pudding

Experiment No.	Factors			Interactions				VIS of pudding, mPa*c per 1 s^{-1}			
	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2\,x_3$	y_1	y_2	y_3	j
1	+	+	+	+	+	+	+	14,420.2	14,481.2	14,512.4	14,471.3
2	–	+	+	–	–	+	–	13,706.5	13,768.7	13,795.3	13,756.8
3	+	–	+	–	+	–	–	14,223.7	14,125.9	14,201.5	14,183.7
4	–	–	+	+	–	–	+	12,758.5	12,875.5	12,789.4	12,807.8
5	+	+	–	+	–	–	–	14,021.7	14,059.5	14,160.3	14,080.5
6	–	+	–	–	+	–	+	13,778.5	13,720.5	13,629.6	13,709.5
7	+	–	–	–	–	+	+	14,089.1	14,028.3	14,146.2	14,087.9
8	–	–	–	+	+	+	–	12,536.3	12,583.6	12,665.4	12,595.1

Table 6

Planning matrix for cream

Experiment No.	Factors			Interactions				VIS of cream, mPa*c per 1 s^{-1}			
	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2\,x_3$	y_1	y_2	y_3	j
1	+	+	+	+	+	+	+	3,740.3	3,795.5	4,684.1	4,073.3
2	–	+	+	–	–	+	–	4,063.5	4,173.1	4,352.7	4,196.4
3	+	–	+	–	+	–	–	3,941.2	3,963.5	3,951.6	3,952.1
4	–	–	+	+	–	–	+	3,963.5	4,078.6	3,997.3	4,013.1
5	+	+	–	+	–	–	–	3,700.5	3,704.4	3,702.4	3,702.4
6	–	+	–	–	+	–	+	4,280.4	4,852.7	4,589.7	4,574.3
7	+	–	–	–	–	+	+	4,725.6	4,685.9	4,703.1	4,704.9
8	–	–	–	+	+	+	–	4,790.9	4,966.7	4,580.7	4,779.4

Table 7

Regression equation coefficients for structured low-calorie dairy desserts

b_0	b_1	b_2	b_3	$b_{1,2}$	$b_{1,3}$	$b_{2,3}$	$b_{1,2,3}$
13711.6	494.3	293,0	93.3	–222.9	28.3	16.2	57.5

The reproducibility variance $S^2_{\{y\}}$ is determined from formula (1)

$$S^2_{\{y\}}=\frac{1}{n\cdot(m-1)}\sum\nolimits_{j=1}^{n}\sum\nolimits_{i=1}^{m}\left(y_{ji}-\overline{y_j}\right)= =\frac{1}{n}\sum_{j=1}^{n}\left[\frac{1}{m-1}\sum_{i=1}^{m}\left(y_{ji}-\overline{y_j}\right)^2\right]=\frac{1}{n}\sum_{j=1}^{n}S_j^2, \quad (1)$$

where S_j^2 – sample variances of experimental results for the jth experiment (j = 1, 2, 3 ... n).

The reproducibility variance was calculated from formula (1)

$$S^2_{\{y\}}=\frac{1}{8}\sum_{j=1}^{8}S_j^2=\frac{29{,}089.6}{8}=3{,}636.2.$$

The mean square deviation of the coefficients was determined from the following formula

$$S_{coef.}=\sqrt{\frac{S^2_{\{y\}}}{n\cdot m}}=\sqrt{\frac{3{,}636.2}{8\cdot 3}}=12.3.$$

From the Student distribution tables [23] for the number of degrees of freedom $\nu = n(m - 1) = 8 \cdot 2 = 16$ at the significance level $\alpha = 0.05$, $t_{crit} = 2.12$ was found.

Therefore, t_{crit}, $S_{coef.} = 2.12 \cdot 12.3 = 26.1$.

Comparing the obtained value $t_{crit}{\cdot}S_{coef} = 26.1$ with the coefficients of the regression equation, it was found that all coefficients, except $b_{2,2}$, are greater in absolute value than 26.1.

Therefore, all coefficients, except $b_{2,3}$, are significant. Assuming $b_{2,3} = 0$, the regression equation in the coded variables is

$$y=13{,}711.6+494.3x_1+293.0x_2+ +93.3x_3-222.9x_1x_2++28.3x_1x_3+57.5x_1x_2x_3. \quad (2)$$

The resulting equation must be checked for adequacy using the Fisher criterion. Since the reproducibility variance was found in the previous paragraph, to determine the calculated value of the criterion $F_{calcul.}$, it is necessary to calculate the residual variance S^2_{resid}. To do this, the value of the studied parameter was found using the obtained regression equation $\tilde{y}_j$ (j = 1,..., 8), substituting +1 or –1 instead of x_i according to the number of the j-th experiment (Table 8).

Table 8

Response function values for each experiment

Experiment No.	x_1	x_2	x_3	x_4	x_5	x_6	$\tilde{y}_i$
1	+1	+1	+1	+1	+1	+1	14,455.1
2	–1	+1	+1	–1	–1	–1	13,740.6
3	+1	–1	+1	–1	+1	–1	14,199.9
4	–1	–1	+1	+1	–1	+1	12,824.0
5	+1	+1	–1	+1	–1	–1	14,096.7
6	–1	+1	–1	–1	+1	+1	13,725.7
7	+1	–1	–1	–1	–1	+1	14,071.7
8	–1	–1	–1	+1	+1	–1	12,578.9

After determining the significant coefficients of the regression equation and calculating the values of the response function $\tilde{y}_i$ (Table 8), the adequacy of the model was checked using the Fisher criterion (Table 9).

Table 9

Assessing the adequacy of the regression equation

Indicator	Value
Residual variance $\left(S^2_{resid}\right)$	6292.1
Degrees of freedom (k_1)	1
Degrees of freedom (k_2)	16
Estimated value of the Fisher criterion ($F_{calcul.}$)	1.73
Tabular value of the Fisher criterion (F_{table}) at significance level α = 0.05	4.49

The residual variance S^2_{resid} was calculated from formula (3)

$$S^2_{resid} = \frac{3}{8-7}\sum_{j=1}^{8}\left(\tilde{y}_j - \overline{y}_j\right)^2. \quad (3)$$

The estimated value of Fisher's test $F_{calcul.}$ is calculated from formula (4)

$$F_{calcul.} = \frac{S^2_{resid}}{S^2_{\{y\}}}. \quad (4)$$

The tabular value of criterion F_{table} is found in the tables of critical points of the Fisher distribution [24] at the significance level $\alpha = 0.05$ for the corresponding degrees of freedom k_1 and k_2 according to formula (5)

$$k_1 = n - r;\ k_2 = n\,(m-1), \quad (5)$$

where n is the number of experiments in the planning matrix, $n = 8$;

m is the number of repeated measurements in each experiment, $m = 3$;

r is the number of significant coefficients of the regression equation, (including the free term b_0), $r = 7$.

Since $F_{calcul.} = 1.73 < F_{table.} = 4.49$, the regression equation (2) is adequate.

After interpreting the obtained model

$$y = 13{,}711.6 + 494.3x_1 + 293.0x_2 + 93.3x_3 - \\ -222.9x_1x_2 + +28.3x_1x_3 + 57.5x_1x_2x_3. \quad (6)$$

From equation (6) it is clear that the factor x_1 – the amount of gelatin added – has the strongest influence, since it has the largest coefficient in absolute value. After it, in terms of the strength of the influence on the response (viscosity) are the amount of starch x_2, the pairwise interaction of factors x_1x_2 (a combination of gelatin and starch), factor x_3 – the amount of rice flour. Then there is a triple interaction of all factors and, finally, the pairwise interaction x_1x_3 – a combination of gelatin and rice flour.

Since the coefficients at x_1, x_2, x_3, x_1x_3, $x_1x_2x_3$ are positive, then with an increase in these factors the response increases, that is, the viscosity increases. The coefficient at x_1x_2 is negative, which means that from the listed interactions the value of the response will increase, and with an increase – it will decrease.

Regression equation in natural variables, substituting their expression in terms of z_i instead of x_i

$$y = 13{,}711.6 + 494.3\frac{z_1-1.0}{0.5} + 293.0\frac{z_2-1.0}{0.5} + \\ +93.3\frac{z_3-1.5}{0.5} - 222.9\frac{z_1-1.0}{0.5}\frac{z_2-1.0}{0.5} + \\ +28.3\frac{z_1-1.0}{0.5}\frac{z_3-1.5}{0.5} + 57.5\frac{z_1-1.0}{0.5}\frac{z_2-1.0}{0.5}\frac{z_3-1.5}{0.5}. \quad (7)$$

After converting equation (4) to natural variables, the equation has the form

$$Y = 10{,}277.868 + 2{,}567.649\cdot z_1 + 2{,}168.049\cdot z_2 + \\ +646.982\cdot z_3 - 1{,}582.132\cdot z_1\cdot z_2 - 458.332\cdot z_1\cdot z_3 - \\ -460.332\cdot z_2\cdot z_3 + 460.332\cdot z_1\cdot z_2\cdot z_3. \quad (8)$$

Mathematical processing of regression equations (2) and (6)–(8) allowed us to establish the optimal concentrations of gelatin and starch in the case of pudding production (Table 10), inulin, and pectin in the case of cream production (Table 11) and their variation to obtain constant viscosity values of structured low-calorie dairy desserts with appropriate organoleptic indicators.

Table 10

Pudding viscosity at optimal concentrations of components in the stabilization system

Content, %			Viscosity of pudding, mPa*s per 1 s^{-1}, based on	
Rice flour	Gelatin	Starch	Buttermilk	Retentate
1.0	0.75	1.45	14,381.7 ± 97.1	25,864.5 ± 99.4
1.5	0.45	1.05	13,619.2 ± 88.5	20,583.6 ± 109.5
2.0	0.25	0.55	12,717.4 ± 107.9	18,220.4 ± 77.9

Table 11

Cream viscosity at optimal concentrations of components in the stabilization system

Content, %			Viscosity of cream, mPa*s per 1 s^{-1}, based on	
DDW	Pectin	Inulin	Buttermilk	Retentate
2.0	0.75	1.45	3,640.2 ± 24.7	4,097.5 ± 42.8
3.0	0.45	1.05	4,583.5 ± 39.9	5,241.5 ± 35.7
4.0	0.25	0.55	5,063.4 ± 38.5	5,836.1 ± 47.9

Analysis of the data given in Table 10 reveals that with an increase in the proportion of rice flour and a simultaneous decrease in the content of gelatin and starch, the viscosity of the pudding decreases. Thus, in the pudding based on buttermilk, the viscosity decreases from 14,381.7 mPa·s to 12,717.4 mPa·s, and on the basis of retentate – from 25,864.5 mPa·s to 18,220.4 mPa·s. Higher viscosity values of the samples based on retentate are due to the increased content of whey proteins, which enhance the structure formation in the dairy system.

The opposite trend is observed for cream (Table 11). Thus, with an increase in the content of DDW, the viscosity of the cream based on buttermilk increases from 3,640.2 mPa·s to 5,063.4 mPa·s and on the basis of retentate – from 4,097.5 to 5,836.1 mPa·s. This confirms the decisive role of whey proteins in the formation of the consistency of the cream, while inulin and pectin perform an auxiliary structuring function.

Our results show that mathematical modeling of the composition of stabilization systems allows for purposeful regulation of the rheological characteristics of structured low-calorie dairy desserts by varying the concentrations of protein and carbohydrate components. The determined optimal ratios of the content of the components of the stabilization systems ensure the formation of the structure of pudding and cream with specified viscosity indicators.

5. 2. Determining the influence of protein and carbohydrate components on the quality of structured low-calorie dairy desserts

The influence of stabilizers and carbohydrate-protein complexes on the organoleptic indicators of structured low-calorie dairy desserts is one of the key aspects of optimizing their composition. It has been shown [25] that the combination of starch with protein components reduces syneresis and improves the consistency of puddings, which directly correlates with an increase in sensory ratings. It has been confirmed [26] that optimizing the composition of the stabilization system allows for a controlled change in the texture of the product and increasing its consumer acceptability.

Therefore, the study of organoleptic indicators provides a comprehensive assessment of product quality and justification of the recipe composition.

The generalized results of the organoleptic evaluation of pudding and cream are shown in Fig. 1.

According to the analysis of organoleptic data (Fig. 1), in terms of taste profiles, almost all pudding and cream samples had good odor and color indicators with no foreign odors. The color was light cream, uniform throughout the mass. It should be noted that the best consistency was in the pudding samples based on retentate using the "gelatin-starch-rice flour" stabilization system and was rated with the highest score of 5 points. The consistency score of the pudding samples based on buttermilk was on average 4.9 points. The best cream sample was found using buttermilk and the "pectin-inulin-whey" stabilization system, all indicators were rated on average at 4.86 points (Fig. 1).

The results of studies of the physicochemical indicators of structured low-calorie dairy desserts with protein and carbohydrate components are given in Table 12.

Table 12

Physicochemical indicators of structured low-calorie dairy desserts based on different milk bases

Indicator ID	Pudding based on			Cream based on		
	Control	Retentate	Buttermilk	Control	Retentate	Buttermilk
Mass fraction of fat, %	3.0 ± 0.5	1.4 ± 0.5	1.0 ± 0.5	2.51 ± 0.5	1.5 ± 0.5	0.7 ± 0.5
Mass fraction of protein, %	2.55 ± 0.27	11.74 ± 0.16	7.83 ± 0.22	2.54 ± 0.12	14.97 ± 0.22	11.53 ± 0.40
Mass fraction of solids, %	27.05 ± 0.32	28.09 ± 0.42	25.11 ± 0.55	31.01 ± 0.44	29.06 ± 0.51	26.31 ± 0.78
Mass fraction of carbohydrates, %, incl.:	12.50 ± 0.45	12.11 ± 0.35	13.35 ± 0.14	23.53 ± 0.26	15.36 ± 0.45	15.81 ± 0.67
sugar, %	11.02 ± 0.33	5.93 ± 0.56	5.95 ± 0.45	8.03 ± 0.51	5.98 ± 0.33	5.93 ± 0.74
Mass fraction of ash, %	2.76 ± 0.51	2.16 ± 0.05	1.81 ± 0.03	2.87 ± 0.09	2.05 ± 0.02	1.77 ± 0.6
Energy value, kcal	125	99	85	127	95	85
Titrated acidity, °T	29 ± 1	29 ± 1	28 ± 1	34 ± 1	32 ± 1	31 ± 1
Active acidity, pH unit	4.4 ± 0.09	4.5 ± 0.15	5.5 ± 0.05	3.9 ± 0.01	3.5 ± 0.01	4.5 ± 0.03
Moisture-retaining capacity, %	100 ± 1			100 ± 1		

Physicochemical indicators of structured low-calorie dairy desserts (puddings and creams) made on the basis of retentate and buttermilk demonstrated significant differences in composition and functional properties (Table 12). Thus, the mass fraction of fat in cream and pudding was 2–3.5 times lower compared to the control.

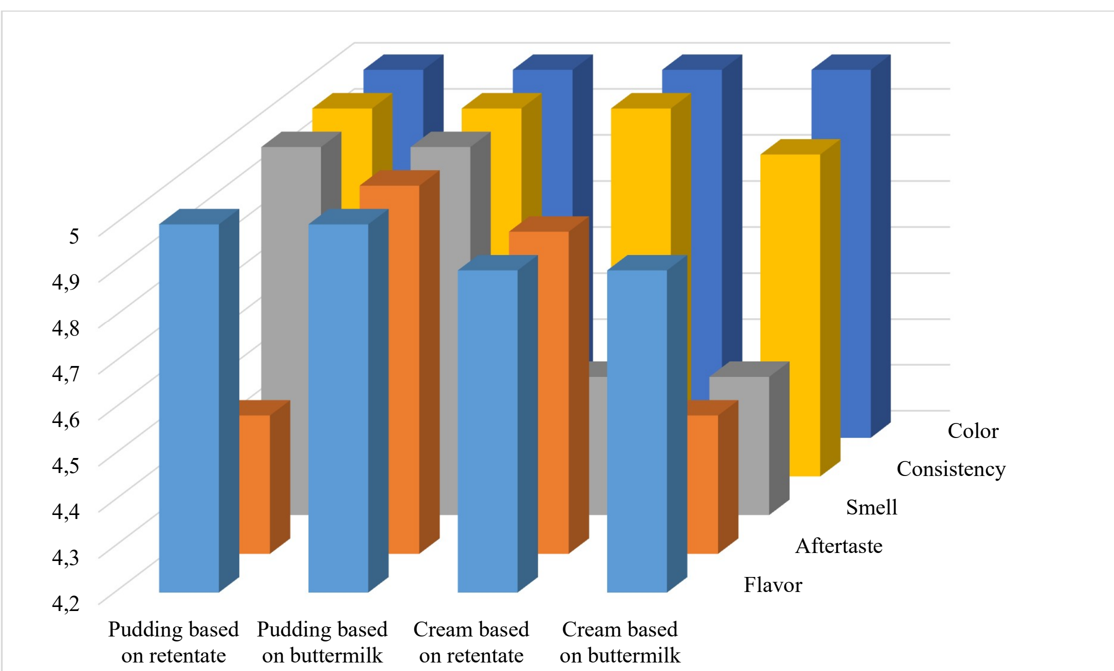

Fig. 1. Organoleptic evaluation of structured low-calorie dairy desserts based on different milk bases

The sugar content in the studied samples was about 6%, which is almost half as much as in the control samples of puddings and a third less than in the control samples of cream. The energy value of the experimental samples of dairy desserts was almost 1.5 times lower than the control samples. This makes it possible to us to classify the developed desserts as low-calorie products.

A significant advantage of structured low-calorie dairy desserts based on secondary dairy raw materials is the high protein content. Namely, based on retentate and buttermilk, the protein content is 5 times and 3 times higher in puddings, respectively, and in creams 4 times than in control.

The moisture-holding capacity of the experimental samples of structured low-calorie dairy desserts was 100%, which indicates sufficient stability of the structure at the selected concentrations of stabilization systems. Our results were correlated with studies on the organoleptic evaluation of dairy desserts (Fig. 1).

A higher content of mineral substances was also established in samples of structured low-calorie dairy desserts based on retentate, which is explained by the increased buffering capacity of the system. This is also confirmed by the indicators of titrated and active acidity of samples of structured low-calorie dairy desserts (Table 12).

6. Discussion of results based on the study on determining the optimal composition of stabilization systems for structured low-calorie dairy desserts

The differences in the values of effective viscosity between puddings and creams (Tables 8, 9) are due to fundamentally different mechanisms of structure formation of the corresponding stabilization systems. In puddings, gelatin plays a dominant role, which at the temperature of thermomechanical processing (80–85°C) denatures and forms a dense three-dimensional gel matrix. The interaction of gelatin with starch, which is described by a negative coefficient through the pair interaction x_1x_2 in the regression equation (2), indicates the competitive nature of water binding between these components. This limits the further increase in viscosity with a simultaneous increase in their concentrations. Instead, rice flour performs mainly a substitute function, increasing the total content of dry substances with simultaneous stabilization of the structure. For creams, the main structure-forming agents are inulin and pectin, the interaction of which with milk protein forms gel structures more gently. In creams, the viscosity values are lower, 3640–5836 mPa·s, compared to 12717–25864 mPa·s in puddings, which corresponds to the patterns described in study [15] for inulin-based systems.

Higher values of the effective viscosity of structured low-calorie dairy desserts based on retentate compared to buttermilk-based samples are explained by the increased concentration of whey proteins in the retentate. Under conditions of thermomechanical processing, they form branched protein-carbohydrate complexes with hydrocolloid components of the stabilization system. This is consistent with the data in work [27], which shows that the increased protein content improves the structure formation and stability of dairy systems. The higher content of minerals in the retentate enhances the ionic strength of the medium and the buffer capacity of the system. This is confirmed by the indicators of active and titrated acidity (Table 10). It also contributes to the stabilization of protein-carbohydrate complexes, similar to the patterns described in [28].

The results of organoleptic evaluation (Fig. 1) correlate with rheological data (Tables 8, 9). Thus, the best organoleptic indicators are demonstrated by samples with optimal viscosity values. This confirms the relationship between structural and mechanical characteristics and consumer acceptability of the product, as shown in study [26]. Reducing the mass fraction of fat in retentate-based desserts (about 6 times) did not lead to a deterioration in organoleptic indicators. This is consistent with the conclusions in [29] that the optimized formulation makes it possible to compensate for the absence of fat due to the functional properties of the protein-carbohydrate complex. Unlike the response surface method [18], applied for one- and two-component systems, the full-factorial experiment 2^3 makes it possible to quantitatively assess the effects of pair and triple interactions. This significantly increases the predictive ability of the model and makes it possible to identify competitive interactions between components that are ignored during conventional one-dimensional formulation selection. The study first applied the mathematical modeling approach specifically for dairy desserts based on secondary dairy raw materials (buttermilk and retentate), which expands the practical value of the obtained regression equations.

However, our study has certain limitations that should be taken into account when interpreting the results and their practical application. The constructed regression equations are adequate only within the studied ranges of concentrations of stabilization system components and under certain conditions of thermomechanical processing; therefore, extrapolation beyond the established limits requires additional verification. The application of the obtained models for other types of dairy raw materials, except for buttermilk and retentate, is incorrect without prior verification. The first-order linear model used with the effects of pair and triple interactions does not take into account possible nonlinear dependences between the concentration of components and viscosity, which may reduce the accuracy of predictions in the case of expanding the ranges of variation of factors; to eliminate this drawback, it is advisable to switch to second-order plans. Since the structure of desserts was evaluated only by one rheological criterion – effective viscosity at a shear rate of 1 s^{-1} – the viscoelastic characteristics and thixotropic behavior of the systems were left out of consideration. Finally, the reproducibility of results in industrial settings may be complicated by the variability of the composition of secondary dairy raw materials and the difficulties of reproducing identical thermomechanical treatment modes on industrial equipment.

The disadvantages of the study include the use of a first-order linear model with interaction effects, which does not take into account possible nonlinear (quadratic) relationships between the concentration of components and the viscosity of dairy desserts. In the case of further expansion of the ranges of variation of factors, this may reduce the accuracy of predictions. This disadvantage can be eliminated by switching to second-order designs, in particular, the central-composition rotatable design or the Box-Behnken design, which will make it possible to evaluate quadratic effects and increase the predicted accuracy of the models. In addition, our study did not take into account the change in rheological parameters of desserts during storage, which limits the completeness of the assessment of the stability of the structure of the developed dairy desserts.

A promising direction is to expand the proposed methodology to other functional ingredients, in particular, carrageenan, xanthan gum, etc., with the aim of comparative analysis of their influence on the rheological and organoleptic characteristics of dairy desserts. From a methodological point of view, research into the microstructure of dairy desserts is of considerable interest. This will make it possible to more deeply understand how the interaction of protein and carbohydrate components at the molecular level determines the consistency and stability of the structure of dairy desserts.

7. Conclusions

1. Based on a full-factorial experiment, regression equations were constructed that describe dependence of the effective viscosity of structured low-calorie dairy desserts on the concentration of the components of the stabilization system. For puddings, the determining factor in the formation of viscosity is gelatin ($b_1 = 494.3$), the effect of which is enhanced by pairwise interaction with starch; for creams, a similar role is played by inulin and pectin. The statistical adequacy of the constructed models was confirmed by the Fisher criterion ($F_{calcul.} = 1.73 < F_{table} = 4.49$, $\alpha = 0.05$). Unlike conventional empirical approaches to the selection of the recipe composition, the proposed methodology allowed us to quantitatively assess the effects of pairwise and triple intercomponent interactions in the stabilization systems of structured low-calorie dairy desserts. This provides the possibility of targeted design of the recipe composition with predicted rheological characteristics, which is a fundamental difference of the proposed approach from one-dimensional optimization methods.

2. The organoleptic, physicochemical, and structural-mechanical indicators of structured low-calorie dairy desserts were studied. At the established optimal concentrations of the components of the stabilization system, the effective viscosity of the buttermilk-based cream was 3640–5063 mPa·s, based on the retentate – 4097–5836 mPa·s; pudding based on buttermilk – 12717–14381 mPa·s, based on the retentate – 18220–25864 mPa·s (at a shear rate of 1 s^{-1}). According to the results of organoleptic evaluation, the highest descriptors were obtained by pudding based on retentate with a stabilization system of "gelatin-starch-rice flour" (5.0 points) and cream based on buttermilk with a stabilization system of "pectin-inulin-whey" (4.86 points). The mass fraction of fat in cream and pudding was 2–3.5 times lower compared to the control. The sugar content in the studied samples was about 6%, which is almost half as much as in the control samples of puddings and a third less than in the control samples of cream. The energy value of the experimental samples of structured low-calorie dairy desserts was almost 1.5 times lower than the control samples. This makes it possible to classify the developed dairy desserts into the category of low-calorie products. This also caused higher structural stability and high moisture retention capacity of the finished product. These differences are explained by the increased buffer capacity of the retentate and the higher concentration of whey proteins, which stabilize the protein-carbohydrate components and contribute to the formation of a denser structure of low-calorie dairy desserts.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

In the process of writing the manuscript, the authors used the artificial intelligence tool ChatGPT (version GPT-5) to check grammar, spelling, punctuation without changing the text, and search for sources using keywords and criteria.

The entire text of the manuscript, including the formulation of the goal, objectives, description of materials and methods, presentation of research results, discussion, and conclusions, was written by the authors independently based on their own experimental data.

Authors' contributions

Iryna Romanchuk: Conceptualization; Methodology, Data Curation, Writing – review & editing, Project administration; **Tetiana Rudakova: Conceptualization, Methodology,** Formal analysis, Investigation, Resources, Data Curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration; **Antonina Minorova: Conceptualization; Methodology;** Data Curation, Writing – review & editing, Project administration; **Viktor Voroshchuk:** Software, Validation, Formal analysis, Data Curation, Writing – review & editing; **Sergiy Narizhnyy:** Formal analysis; Resources, Data Curation, Writing – review & editing, Funding acquisition; **Lesia Korol-Bezpala:** Formal analysis, Resources, Data Curation, Writing – review & editing, Funding acquisition; **Liudmyla Zahorui:** Formal analysis, Resources, Data Curation, Writing – review & editing, Funding acquisition.

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