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DETERMINING THE EFFECT OF HEAT TREATMENT ON THE INDICATORS OF DEMINERALIZED WHEY LIQUID CONCENTRATES

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This study investigates the technology of liquid demineralized whey concentrates. The task addressed is to determine rational modes for the thermal treatment of liquid demineralized whey concentrates in order to improve their functional and technological properties.

Liquid whey concentrates were pasteurized under the following modes: 1 (temperature – 70 ± 2°C, duration – 3–5 min), 2 (temperature – 80 ± 2°C, duration – 3–5 min), 3 (temperature – 90 ± 2°C, duration – 3–5 min).

With an increase in the dry matter content from 10 to 40% in the concentrates, the density increased, the water activity and surface tension decreased, and the active acidity stabilized. The choice of mode 2 of heat treatment for a concentrate with a mass fraction of dry matter of 40% turned out to be the most rational since it provided a balance between high pasteurization efficiency and preservation of the qualitative characteristics of the studied sample.

With increasing concentration of dry matter, a significant increase in effective viscosity was observed. For 40% concentrate, mode 2 provides the maximum level of thixotropy – up to 75%, which indicates significant elasticity and technological stability of the product.

Analyzing the amino acid composition of 40% concentrate under different pasteurization modes, a clear trend of decreasing the content of all amino acids with increasing heat treatment temperature was observed.

The results could be used as recommendations for adjusting technological parameters to obtain stable whey concentrates. The pasteurized concentrates obtained are semi-finished products that could be used in the food industry

Keywords: whey, heat treatment, water activity, surface tension, effective viscosity, thixotropy of the system, quality indicators, amino acid composition

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1. Introduction

The market for milk protein ingredients derived from whey is dynamically evolving due to the increased demand for high-protein food products and the active introduction of secondary dairy resources into technological processes. Demineralized whey, as a promising raw material, attracts the attention of manufacturers of functional food products because of the reduced content of mineral salts and the possibility of its use in a wide range of dairy and milk-containing products. One of the directions for effective use of demineralized whey is the production of liquid concentrates with specified rheological and chemical properties, which can serve as the basis or ingredients in the production of ice cream, desserts, drinks, sauces [1].

However, the formation of the corresponding physicochemical and functional and technological properties of liquid concentrates largely depends on the parameters of heat treatment, which is a mandatory stage for ensuring the microbiological safety of the product. Excessive heat treatment can lead to protein denaturation, viscosity changes, sediment formation, darkening and deterioration of the functional characteristics of the concentrate [2, 3]. In contrast, insufficient heat treatment does not guarantee product stability during storage. Therefore, determining rational heat treatment regimes is an important condition for preserving the quality indicators of concentrates and increasing their nutritional value.

The effect of heat treatment on milk, including the quality of protein, fats, minerals, vitamins, physical appearance, and taste, has been the subject of intensive research over the past few decades [4]. However, the effect of elevated temperature on the quality indicators of liquid whey concentrates has not been studied in detail. In particular, rational pasteurization regimes have not been proven in terms of their effect on the organoleptic, rheological, and physicochemical properties of liquid demineralized whey concentrates, especially when they are subsequently used in high-protein food systems. That is why it is relevant to study the changes in the parameters of demineralized whey concentrates under the influence of different heat treatment modes in order to substantiate rational technological parameters.

2. Literature review and problem statement

Pasteurization of milk involves heating it to a sufficient temperature and holding it for a certain time to inactivate and destroy pathogenic microorganisms and extend the shelf life of the finished product. The two most common types of pasteurization are short-time pasteurization and ultra-high-temperature pasteurization. In the short-time treatment process, milk is heated to a minimum of 72°C for 15 seconds, while in ultra-high-temperature pasteurization, milk is held at a temperature of 135–140°C for 1–2 seconds [5]. Such heat treatment modes ensure the microbiological safety of the product but can significantly reduce its nutritional value and characteristics.

Thus, in [6] it was reported that high-temperature processing, especially ultra-high-temperature pasteurization, causes a number of consequences for milk, such as the loss of available lysine, as well as protein aggregation and denaturation. Similar effects were reported in [7], in which it was noted that in addition to modifications of the functional properties of milk proteins, many chemical changes may occur. These changes inevitably affect the emulsifying and foaming properties of dairy products based on thermally treated milk. At the same time, studies [6, 7] are limited to the analysis of changes in milk and do not take into account the high concentration of solids, which can significantly change the course of the thermal treatment process.

Increasing the duration of heat treatment also increases the degree of whey protein denaturation and promotes the formation of the whey protein-casein complex in milk. It is known that the denaturation of thermolabile whey proteins begins when the temperature rises to > ~62 (α-la) and ~75°C (β-lg) [8], which generally indicates a low thermal stability of whey proteins during heat treatment of milk [9]. However, in [8, 9], protein denaturation was studied in food systems with a low content of dry matter, while in concentrated solutions (30–40%) the interactions between protein components are significantly different. In addition, the studies do not cover the effect of heat treatment on the structural and mechanical characteristics of such systems.

In [10] it was reported that whey proteins are reversibly denatured at temperatures between 55°C and 65°C and irreversibly denatured at temperatures above 65–70°C. However, study [10] does not consider changes in amino acid composition and functional and technological properties after pasteurization.

The results of another study [11] indicate that heat treatment at temperatures above 60°C leads to denaturation of whey protein in milk, which is associated with the formation of a whey protein polymer alone or in combination with casein. Almost all whey protein was denatured when milk was heated to 95°C for 10 min. The results from [11] do not investigate how denaturation manifests itself in liquid concentrates with a mass fraction of solids of 40%, where protein fractions may behave differently.

An option to overcome these difficulties may be the use of short-term processing at a certain temperature, which would enable the preservation of the functional properties of the input raw materials. This approach was used in work [12], which focused on studying the effect of heat treatment on the properties of milk proteins. Variable heat treatment modes were used: experiment 1 – heating time 10 min, 20 min, and 30 min; heating temperature 65°C, 75°C, 85°C, 95°C, 100°C; experiment 2 – heating time: 5, 10, 15, 20, 25, 30 min, heating temperature: 75°C, 85°C, 95°C. Based on these results, it was proven that the increase in the degree of denaturation in whole protein fractions increases with increasing pasteurization temperature from 65°C to 95°C. The same effect was also observed when the pasteurization time was increased from 5 to 30 min, indicating the feasibility of using a regime with the minimum possible duration of heat treatment. In [12], the heat treatment of milk was investigated but not of whey concentrates, and no comparison was made between different levels of dry matter concentration in food systems. However, if the pasteurization time is reduced, the degree of protein denaturation may decrease [13].

Therefore, it may be appropriate to investigate the possibility of using pasteurization regimes with a higher processing temperature than 65°C. According to [14], it was found that thermal pasteurization of cow's milk can lead to denaturation of secondary whey proteins and loss of their bioactivity. Denaturation of whey proteins in skim milk was studied at different combinations of temperature (72, 75, or 78°C) and time (0–300 s). The results of sodium dodecyl sulfate polyacrylamide gel electrophoresis showed that denaturation of all proteins occurred at 72°C and progressed with increasing temperature and duration of treatment. Data [13, 14] confirm the thermosensitivity of bioactive proteins but they do not take into account changes in surface tension, water activity, and rheological parameters of concentrates. Accordingly, the problem of a comprehensive assessment of heat treatment on concentrated systems remains an open question.

All this gives grounds to argue that it is advisable to conduct a study on the justification of heat treatment regimes for liquid demineralized whey concentrates.

3. The aim and objectives of the study

The aim of our work is to determine the effect of heat treatment under variable regimes on the parameters of liquid concentrates of demineralized whey. This will provide an opportunity to substantiate rational heat treatment regimes for the further use of liquid concentrates of whey in the technologies of dairy and milk-containing products.

To achieve this goal, the following tasks were set:

– to determine the change in the main physicochemical parameters of liquid concentrates of demineralized whey as a result of the influence of heat treatment under different regimes;

– to determine the effective viscosity of the experimental systems and their thixotropic ability;

– to determine the change in the amino acid composition of liquid concentrates of demineralized whey under the influence of heat treatment.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the technology of liquid demineralized whey concentrates.

The principal hypothesis of the study assumes that variable heat treatment modes of liquid demineralized whey concentrates could significantly affect their physicochemical properties and amino acid composition. This would make it possible to substantiate rational treatment modes to increase the functionality of concentrates for further use in the food industry.

At the stage of conducting the research, it was assumed that changing the heat treatment temperature would have a predictable and controlled effect on the structure of the concentrates and their rheological characteristics. It was predicted that the effect of heat treatment on the amino acid composition of the concentrates could be significant but would not lead to complete denaturation of protein components. The results to be obtained will be applicable to improving the technological parameters of the production of dairy and milk-containing products using demineralized whey concentrates.

To simplify the study, a limited set of the most well-known pasteurization modes with a fixed duration of heat treatment was selected. This approach narrowed the variability of the studied parameters, which allowed us to focus on the systematic study of the influence of these standard heat treatment modes on the properties of concentrates.

4. 2. Materials and equipment used in the experiment

As the input raw material for the production of concentrates, dry demineralized whey with a demineralization level of 90% (AT "Milk Alliance", Ukraine) was selected, which contains, in terms of dry matter: ash – no more than 2.5%, lactose – no less than 79%, protein – no less than 10.7%. The solubility index of dry demineralized whey – 0.5 cm^3 of raw sediment.

Dry demineralized whey was restored in drinking water at a temperature of 40–45°C to obtain concentrates with a mass fraction of dry matter from 10 to 40%. The concentrates were filtered, pasteurized under variable conditions, and cooled.

Pasteurization of liquid whey concentrates was carried out according to the following modes:

– mode 1: temperature – 70 ± 2°C, duration – 3–5 min;
– mode 2: temperature – 80 ± 2°C, duration – 3–5 min;
– mode 3: temperature – 90 ± 2°C, duration – 3–5 min.

The above pasteurization modes were selected for the study because they cover a rational range of heat treatment of liquid whey concentrates, which enables the preservation of the quality characteristics of the product with proper microbiological purity. Mode 1 meets the minimum standards of pasteurization, which preserves the maximum biological value of the protein, mode 2 is an intermediate mode, and mode 3 is the maximum permissible temperature at which maximum microbiological safety is achieved, but the risk of thermal denaturation of proteins increases.

The unified duration of heat treatment for all three modes is 3–5 min, which is sufficient to ensure the stable destruction of harmful microorganisms, and also allows minimizing the loss of nutritional value of the concentrate. This approach enables comparability of results and technological efficiency of the pasteurization process.

4. 3. Methods for investigating whey concentrates

The relative density was investigated by the pycnometric method, which involves determining the mass of a certain volume of the test liquid using a pycnometer and subsequent comparison with the mass of the same amount of water [15].

The water activity in whey concentrates and ice cream mixes was determined on the water activity analyzer "HygroLab 2" in the measurement range of 0–1 Aw (0–100% rh).

The active acidity was measured by inserting the electrodes of the potentiometric analyzer into the concentrates at a temperature of 20°C.

The surface tension was determined by the stalagmometric method, which is based on measuring the volume of liquid droplets flowing from the capillary under the action of gravity. Based on the number of drops of the test and reference liquid (water), the surface tension of the samples was calculated [16].

Viscosity characteristics were determined on a rotational viscometer "Rheotest II" with a "cylinder-cylinder" measuring system by recording deformation kinetics curves. The study was carried out at a temperature of 20°C. Shear stress τ (Pa) was measured at twelve values of the shear rate gradient D in the range from 3 to 1312.2 s^{-1} in the forward and reverse direction. The maximum effective viscosity of a practically undamaged structure ($\gamma = 3$ s^{-1}), the minimum effective viscosity of a severely damaged structure ($\gamma = 1312.2$ s^{-1}) and the effective viscosity of the restored structure ($\gamma = 3$ s^{-1}) were recorded. The degree of recovery of the structure of concentrates (thixotropic ability) was determined in percent by the difference in the effective viscosity values of the practically undamaged structure at the beginning and end of the measurement at a shear rate gradient ($\gamma = 3$ s^{-1}) [17].

The amino acid composition was studied by ion-exchange liquid column chromatography on an automatic amino acid analyzer T339 [18].

Statistical analysis was performed using the Statistika 10 program. The data were expressed as the mean value with standard deviation for triplicate measurements. Differences were considered reliable at a validity of $\alpha = 0.95$. The construction of rheograms of the flow of ice cream mixtures was carried out in the Microsoft Excel 2016 environment. To ensure the reliability of our results, experiments were carried out three times.

5. Results of studies on the influence of heat treatment on the indicators of concentrates

5. 1. Results of determining the change in physicochemical indicators of concentrates under the influence of heat treatment

The results of studies on the physicochemical indicators of concentrates with different mass fractions of dry substances (10, 20, 30, and 40%) after heat treatment indicate a significant influence of both the degree of concentration and the temperature of pasteurization on the characteristics of these food systems.

In particular, the relative density of concentrates increases with an increase in the mass fraction of dry substances due to an increase in the concentration of dissolved components (Table 1). The highest density values were recorded for samples with 40% dry substances, where the difference between the pasteurization modes is the most significant. Thus, mode 1 (1130 kg/m^3) provides the highest indicators; however, mode 2 (1118.9 kg/m^3) is also characterized by high density and at the same time can provide more effective heat treatment conditions.

Table 1

Relative density, kg/cm^3 ($p \leq 0.05$, $n = 3$)

Heat treatment	Concentrate with a mass fraction of solids, %			
	10	20	30	40
No treatment	1027.5 ± 0.5	1048.1 ± 0.6	1063.9 ± 0.7	1078.3 ± 0.8
Mode 1	1030.8 ± 0.6	1065.9 ± 0.8	1100.0 ± 1.0	1130.0 ± 1.2
Mode 2	1027.5 ± 0.5	1060.2 ± 0.7	1095.5 ± 1.0	1118.9 ± 1.1
Mode 3	1032.6 ± 0.6	1058.8 ± 0.7	1083.3 ± 0.9	1103.7 ± 1.0

Water activity decreased with increasing dry matter concentration under all regimes, which will contribute to increasing the microbiological stability of the concentrates (Table 2). The lowest water activity values were observed at a dry matter mass fraction of 40%, in particular 0.924 under regime 2 and 0.911 under regime 3.

Table 2

Water activity, units ($p \leq 0.05$, $n = 3$)

Heat treatment	Concentrate with a mass fraction of solids, %			
	10	20	30	40
No treatment	0.983 ± 0.002	0.974 ± 0.003	0.961 ± 0.003	0.944 ± 0.004
Mode 1	0.980 ± 0.002	0.968 ± 0.002	0.952 ± 0.003	0.934 ± 0.001
Mode 2	0.977 ± 0.002	0.961 ± 0.003	0.946 ± 0.002	0.924 ± 0.003
Mode 3	0.974 ± 0.003	0.954 ± 0.001	0.934 ± 0.004	0.911 ± 0.004

As for active acidity, with an increase in the concentration of dry matter, it decreases somewhat, but the difference between the pasteurization modes is minimal, which indicates the stability of the acid-base balance of the concentrates (Table 3).

Table 3

Active acidity, units pH ($p \leq 0.05$, $n = 3$)

Heat treatment	Concentrate with a mass fraction of solids, %			
	10	20	30	40
No treatment	6.49 ± 0.02	6.42 ± 0.01	6.36 ± 0.02	6.18 ± 0.03
Mode 1	6.44 ± 0.03	6.39 ± 0.02	6.36 ± 0.01	6.22 ± 0.02
Mode 2	6.41 ± 0.02	6.38 ± 0.03	6.37 ± 0.02	6.25 ± 0.01
Mode 3	6.38 ± 0.01	6.35 ± 0.02	6.39 ± 0.03	6.28 ± 0.02

Surface tension decreased with increasing solids concentration and processing temperature (Table 4). The lowest surface tension values were found at 40% solids under modes 2 and 3, which will positively affect the functional properties of the concentrate, in particular its emulsification and solubility.

Table 4

Surface tension, mN/m ($p \leq 0.05$, $n = 3$)

Heat treatment	Concentrate with a mass fraction of solids, %			
	10	20	30	40
No treatment	73.96 ± 1.12	69.87 ± 0.98	67.95 ± 1.05	65.79 ± 1.08
Mode 1	75.83 ± 1.15	68.41 ± 1.02	62.72 ± 0.93	60.54 ± 0.91
Mode 2	76.54 ± 1.07	65.47 ± 1.03	58.19 ± 0.85	55.14 ± 0.82
Mode 3	79.70 ± 1.21	62.87 ± 0.99	54.87 ± 0.79	52.77 ± 0.84

Considering the obtained data on the physicochemical parameters of the concentrates, the presence of 40% dry matter in the solutions has a number of advantages: high density, reduced water activity to increase stability during storage, stable active acidity at a high concentration of dry matter. At the same time, the choice of heat treatment mode 2 for this concentration is rational since it provides a balance between sufficient pasteurization and preservation of quality characteristics. This mode allows one to avoid excessive denaturation of proteins and maintain stable acidity, while maintaining a low level of surface tension and moderate water activity.

5. 2. Results of determining the rheological characteristics under the influence of heat treatment

Increasing the mass fraction of dry matter in whey concentrates contributes to an increase in the effective viscosity index both at low ($\gamma = 3$ s^{-1}) and high ($\gamma = 1312.2$ s^{-1}) shear rate gradient. The rheological characteristics of whey concentrates before and after heat treatment are given in Table 5.

At low shear rate gradient, the viscosity of the 40% concentrate increases from 250.11 mPa·s for the native form to 309.9–350.1 mPa·s for the heat-treated samples. The use of modes 2 and 3 increases the viscosity of the concentrates by 16.9 and 17.3 mPa·s, respectively, at high shear rate gradient. This trend indicates that an increase in the concentration of solids has a positive effect on the ability of bonds to restore the structure after destruction.

A correlation is observed between the thixotropy indicators and the time of ultimate destruction of the structure of these food systems. An increase in the concentration of solids and the intensity of the heat treatment modes increases the degree of structural restoration and the resistance of the samples to mechanical loading expressed in the time of destruction. The destruction of the structure for the 40% concentrate after treatment under mode 2 occurs within 3.1 min and for mode 3 within 3.25 min, which significantly exceeds the value for the untreated concentrate (2.29 min).

Thixotropy of whey concentrates increases with increasing processing temperature and concentration of dry matter. However, the greatest ability to restore the structure is observed after processing under mode 2 (75%). Under mode 3, there is a slight decrease in this indicator (74.8%). This indicates the elasticity of the formed bonds, which is an indicator of the technological stability of food systems for further use in food production technologies.

Analysis of the rheological characteristics of whey concentrates reveals the prospects of a concentrate with a mass fraction of 40% after heat treatment at a temperature of (80 ± 2)°C with a holding time of (3–5) minutes. This combination of dry matter concentration and processing mode ensures the production of a semi-finished product with pronounced technological properties. In particular, high viscosity, degree of structure restoration, and resistance to mechanical loads. Such indicators are especially important in the context of further technological processing, which involves additional effects on the structure of the product during passage through pipelines, dosing, mixing, and packaging.

Table 5

Rheological characteristics of liquid whey concentrates

Mass fraction of dry matter in the concentrate, %	Effective viscosity (mPa·s) under variable shear rate gradient			Time of ultimate structural failure (γ = 1312.2 s^{-1}), min	Degree of structure recovery, %
	γ = 3 s^{-1} (direct course)	γ = 1312,2 s^{-1}	γ = 3 s^{-1} (reverse course)		
No treatment					
10	102.5 ± 1.2	7.9 ± 0.2	53.0 ± 0.9	2.43 ± 0.1	48.5 ± 1.4
20	170.1 ± 1.8	8.4 ± 0.2	94.8 ± 1.2	2.08 ± 0.1	52.9 ± 1.3
30	210.3 ± 2.2	9.9 ± 0.3	139.8 ± 2.0	1.97 ± 0.1	59.8 ± 1.5
40	250.1 ± 2.6	11.9 ± 0.4	179.6 ± 3.1	2.29 ± 0.1	69.9 ± 1.5
Mode 1					
10	125.0 ± 1.3	8.97 ± 0.2	64.8 ± 1.0	2.67 ± 0.1	61.9 ± 1.5
20	195.2 ± 2.0	10.53 ± 0.2	114.8 ± 1.8	2.43 ± 0.1	64.9 ± 1.4
30	269.8 ± 2.9	13.98 ± 0.2	184.9 ± 1.6	2.19 ± 0.1	69.9 ± 1.4
40	309.9 ± 3.0	16.48 ± 0.4	229.7 ± 2.9	2.82 ± 0.2	74.1 ± 1.9
Mode 2					
10	134.8 ± 1.1	9.4 ± 0.3	69.8 ± 1.0	2.7 ± 0.1	63.0 ± 1.5
20	209.9 ± 2.5	11.0 ± 0.2	120.1 ± 1.9	2.4 ± 0.1	65.9 ± 1.4
30	289.5 ± 3.0	14.5 ± 0.2	189.8 ± 1.4	2.3 ± 0.2	71.8 ± 1.5
40	334.8 ± 2.0	16.9 ± 0.3	239.8 ± 3.4	3.1 ± 0.0	75.0 ± 2.0
Mode 3					
10	139.9 ± 1.2	10.0 ± 0.2	74.8 ± 1.0	2.97 ± 0.1	64.97 ± 1.5
20	229.1 ± 2.4	11.7 ± 0.2	124.7 ± 1.9	2.57 ± 0.1	67.97 ± 1.5
30	304.9 ± 3.0	14.9 ± 0.3	194.6 ± 2.4	2.44 ± 0.2	73.05 ± 1.4
40	350.1 ± 2.8	17.3 ± 0.44	244.8 ± 3.5	3.25 ± 0.1	74.98 ± 2.0

5. 3. Results of determining the amino acid composition under the influence of heat treatment

According to the results of our analysis of the amino acid composition of 40% concentrates, there is a clear trend of decreasing the content of all amino acids in them with increasing heat treatment temperature (Table 6).

Table 6

Amino acid content, mg/100 g

Amino acid ІІІВ	Heat treatment mode			
	No treatment	Mode 1	Mode 2	Mode 3
Lysine	0.32	0.30	0.27	0.22
Histidine	0.07	0.06	0.05	0.04
Arginine	0.12	0.11	0.10	0.08
Aspartic acid	0.38	0.35	0.32	0.26
Threonine	0.22	0.20	0.18	0.14
Serine	0.17	0.16	0.14	0.11
Glutamic acid	0.50	0.47	0.44	0.37
Proline	0.22	0.21	0.19	0.15
Glycine	0.10	0.09	0.08	0.06
Alanine	0.18	0.17	0.15	0.12
Cystine	0.09	0.08	0.07	0.05
Valine	0.10	0.09	0.09	0.07
Methionine	0.03	0.03	0.03	0.02
Isoleucine	0.13	0.12	0.11	0.08
Leucine	0.33	0.31	0.29	0.22
Tyrosine	0.10	0.09	0.08	0.06
Phenylalanine	0.13	0.12	0.11	0.08
Total	3.30	3.05	2.80	2.12

The highest values were recorded in the untreated sample (3.30 mg total per 100 g), and the lowest under mode 3 (2.12 mg total per 100 g). Particularly notable is the decrease in the content of lysine, which is an essential amino acid, from 0.32 to 0.22 mg/100 g, which indicates the heat sensitivity of the whey protein components. The decrease in other amino acids (aspartic acid, glutamic acid, threonine, leucine) also reflects some denaturation or degradation of proteins under the influence of heat treatment.

Mode 2, compared to modes 1 and 3, demonstrates a balance between the preservation of the amino acid profile (2.80 mg total per 100 g) and the efficiency of pasteurization, reducing the risk of microbiological contamination while preserving most of the nutritional value of the protein.

Therefore, the choice of mode 2 is appropriate from the point of view of the balance between technological safety and preservation of the biological value of the concentrate, which is critical for the further use of the concentrate as a protein fortifier in food products.

6. Investigating the influence of heat treatment on the indicators of liquid whey concentrates: results and summary

Our results show that an increase in the pasteurization temperature and the concentration of dry substances led to an increase in the relative density and a decrease in the activity of water in the concentrate (Tables 1, 2). This is explained by the fact that an increase in the mass fraction of dry substances reduces the mass fraction of free water in the system, which reduces its activity, while in [19] changes occurred already at the stage of storage of finished concentrates, where an increase in water activity was observed. Thus, unlike [19], where the main mechanism was secondary reactions during storage, in this case the decrease in water activity is explained by the direct influence of the concentration of dry substances and heat treatment during pasteurization.

Regarding the stability of the acid-base balance of concentrates (Table 3), it was found that pasteurization and homogenization cause changes in the secondary structure of proteins, which determines their ability to interact with other components of the system. This is confirmed by the findings in [5]; however, in this case, the preservation of pH stability under conditions of increased concentrations is explained precisely by the combined effect of temperature and high dry matter content. In contrast to the results reported in [5], which considered only structural changes in proteins, it was found that it is the combination of concentration and temperature that provides greater stability of food systems.

The increase in the effective viscosity and thixotropy of whey concentrates occurs due to partial thermal denaturation of proteins, which leads to the formation of a denser protein network, the bonds of which have better interaction with each other. In studies [20, 21], a change in rheological characteristics in finished dairy products was considered, while in our work it was investigated in whey concentrates with different mass fractions of dry matter. The positive dynamics revealed indicates the advantage of increasing the content of dry matter in concentrated systems through the use of dry demineralized whey. This approach allows for predictable regulation of the technological stability of these semi-finished products, in particular, thixotropy, elasticity of the structure and consistency of the finished product.

An increase in the temperature of heat treatment affects the reduction of the content of amino acids, namely lysine, aspartic and glutamic acids (Table 6). This phenomenon is justified by their high thermal lability, resulting in the destruction of peptide bonds. Previously identified patterns investigated the effect of temperature treatment on the amino acid composition [13] and microbiological risks [22, 23]. However, in the course of our experiment, amino acids were quantified specifically for food systems by type of concentrated whey. The data obtained allow us to analyze the permissible threshold of heat treatment for whey concentrates, which ensures maximum preservation of amino acid content with proper microbiological safety.

As a result of heat treatment, the total content of amino acids decreases from 3.30 mg (unprocessed concentrates) to 2.12 mg (mode 3), which is consistent with previously identified patterns [24]. The advantage of our work is the confirmation of the thermolability of amino acids in the composition of whey concentrates, in particular, the identification of those that have the greatest sensitivity to heat treatment. Thus, it becomes possible to introduce the effect on the biological value of the food system as a criterion for choosing the heat treatment mode.

Work performed is a comprehensive study on the technological and functional properties of whey concentrates under the influence of heat treatment. Analysis of the influence of different pasteurization modes on the physicochemical and rheological properties, as well as the content of amino acids allows us to justify the choice of mode 2 (temperature 80 ± 2°C with a holding time of 3–5 min). This approach ensures the production of food systems with pronounced technological functions with the minimum possible impact on the nutritional value.

The limitation of the study is that a set of standard heat treatment modes with a fixed duration was considered, which does not make it possible to take into account the influence of other technological parameters.

Among the potential shortcomings of the study, it can be noted that the experiments were conducted under laboratory conditions, which requires additional testing under industrial conditions.

Prospects for further research are related to the expansion of heat treatment parameters, in particular, the study of variable duration of the heat regime and different temperature profiles. An important direction is the conduct of industrial testing to verify the reproducibility of laboratory results and assess the economic efficiency of the proposed technology. It is advisable to conduct an in-depth study of microbiological indicators, the impact on nutritional value and structural and mechanical characteristics of the product. It is also considered promising to expand the scope of application of the methodology to various types of dairy raw materials and potential implementation in other food technologies. Such a comprehensive approach could make it possible not only to verify our scientific results but also significantly expand their practical use.

7. Conclusions

1. With an increase in the dry matter content from 10 to 40%, the density in the concentrates increased, while the water activity and surface tension decreased, and the active acidity stabilized. That is why, for concentrates with a mass fraction of dry matter of 10–20%, it is advisable to use mode 3 (temperature – 90 ± 2°C, duration – 3–5 min), and for concentrates with a mass fraction of dry matter of 30–40%, mode 2 is used, which avoids excessive denaturation of proteins and ensures the preservation of stable acidity, while maintaining a low level of surface tension and moderate water activity.

2. With an increase in the dry matter concentration, a significant increase in the effective viscosity of concentrates is observed at a low shear rate gradient. Demineralized whey concentrate with a mass fraction of dry matter of 40% is the most promising for use in food products due to the formation of a stable and elastic structure. At the same time, mode 2 (temperature – 80 ± 2°C, duration – 3–5 min) provides high effective viscosity, maximum degree of recovery, and provides a balance between preserving physicochemical characteristics and technological stability of the product.

3. The highest values of amino acids were recorded in the sample without treatment (3.30 mg total per 100 g), and the lowest – under mode 3 (2.12 mg total per 100 g). Therefore, mode 2, compared to modes 1 and 3, is the most appropriate for heat treatment of whey concentrate with a mass fraction of dry matter of 40%, since it demonstrates a balance between preserving the amino acid profile (2.80 mg total per 100 g) and the efficiency of pasteurization.

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, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors declare that generative artificial intelligence tools were used exclusively for language editing, grammar checking, and technical formatting of the manuscript under full human control. Artificial intelligence was not used to create, process, or interpret scientific data, form conclusions or other elements of the scientific results of the article. Tool used: ChatGPT (OpenAI GPT-5, version 2025). The authors bear full responsibility for the content, reliability, and scientific correctness of the submitted material.

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