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Optimisation of parameters for obtaining milk-plant concentrates

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Abstract. A priority direction in the dairy processing industry is the development of innovative resource-saving technologies that enable raw material conservation, increased yield, and expanded product range. In particular, there is a growing demand for plant-based milk analogs in mixtures for producing milk-plant concentrates using accelerated technologies. The study aimed to determine the optimal parameters of the thermoacid coagulation process for milk-plant protein mixtures to obtain milk-plant concentrates and analyse their impact on the yield and qualitative characteristics of the final product. Milk-plant concentrates were obtained by thermoacid precipitation of proteins from a milk-plant mixture. The Box-Wilson central composite design method was used to optimise the parameters of concentrate production. It was established that thermoacid precipitation of proteins in a milk-plant mixture containing 35% whey-plant suspension with a water-to-solid ratio of 1:3 and a self-pressing duration of 30 min ensured a 36% transition rate of both milk and plant proteins into the concentrate. These parameters were 8-12% higher than those for protein precipitation from a mixture of skim milk and whey-plant suspension (20%) with water-to-solid ratios of 1:5 and 1:7. The addition of a 20% whey-plant suspension with a water-to-solid ratio of 1:7 and a curd self-pressing duration of 10 min resulted in the least protein destabilisation and the highest moisture content (78%) in the milk-plant concentrates. Analysis of the active acidity (pH) of the concentrates revealed a general trend: as the proportion of whey-plant suspension in the mixture increased from 20% to 40% and its water-to-solid ratio changed from 1:7 to 1:3, the pH decreased linearly. The lowest impact on water-holding capacity (72%) was observed under the following conditions: 20% whey-plant suspension, 1:7 water-to-solid ratio, and 10 min self-pressing duration. The obtained results allow for the regulation of qualitative indicators of milk-plant concentrates depending on their intended use, enabling the diversification of protein products with controlled moisture content, water-holding capacity, and active acidity

Keywords: milk; *Arachis hypogaea*; thermoacid coagulation; mathematical modeling; quality indicators

Introduction

The growing interest in a healthy lifestyle has contributed to the increasing popularity of plant-based diets. The food industry is actively responding to this demand by developing new product categories. Among these are alternative versions of traditional foods for vegans and vegetarians, including meat substitutes, plant-based eggs, mayonnaise, ready-made meals, sauces, and plant-based milk. Notably, plant-based dairy products have gained significant consumer popularity (Tachie *et al.*, 2023). According to Y. Motuzka & A. Koshelnyk (2019), the modern dairy industry in Ukraine exhibits a trend toward increasing the production of low-fat products, as well as incorporating alternative ingredients and various additives to enhance

taste, aroma, and texture. These changes align with global trends; however, in the Ukrainian context, they are primarily driven by the shortage of natural dairy raw materials. One potential solution to this issue is the incorporation of additional plant-based sources of protein and fat in dairy processing, as well as the more efficient utilisation of secondary dairy raw materials.

In recent years, the food market has shown a growing trend in expanding the range of plant-based protein products. This is driven by the search for new and renewable raw material sources (Kushnir & Nikolaienko, 2023). Particular attention has been given to the development of plant-based milk analogs (Sharma, 2023). According to F. Reyes-Jurado *et*

al. (2021), the increasing popularity of plant-based milk can be attributed to certain consumer groups preferring it over cow's milk due to its taste characteristics and rich composition, which includes natural plant-derived vitamins, minerals, and dietary fiber. Scientific research is actively exploring the feasibility of producing dairy products using plant-based ingredients, involving the partial or complete replacement of dairy components. Researchers utilise proteins from various grains and legumes, such as soy, chickpeas, peas, rice, and flaxseed, aiming to identify alternative ingredients that reduce dairy protein consumption while maintaining balanced nutritional value (Ayodeji *et al.*, 2020; Golchin *et al.*, 2023; Grasso *et al.*, 2023).

Legumes such as soy, peanut (*Arachis hypogaea*), and lupin milk serve as valuable ingredients for food enrichment (Goldstein & Reifen, 2022). Investigating their potential applications in dairy product manufacturing is a promising field, considering their unique chemical composition and properties (Gharibzahedi & Smith, 2021). Legumes are known for their high protein content with significant biological value, as well as carbohydrates, minerals (especially calcium and iron), and vitamins (thiamine and niacin). Furthermore, as noted by M. Carbonaro and A. Nucara (2022), legumes have a low-fat content and a low glycemic index (GI 31) due to their high fiber, oligosaccharide, and slowly digestible starch content. Additionally, research by M. Pina-Pérez & M. Ferrús Pérez (2018) indicates that legumes possess antioxidant, antimicrobial, and anti-inflammatory properties.

The analysis of both Ukrainian and international scientific studies suggests that the development of milk-plant products should prioritise raw materials that are either traditional or widely available in a specific region. In Ukraine, peanut cultivation (*Arachis hypogaea*) is gaining popularity due to its high nutritional value, particularly its easily digestible protein and fat content. The protein composition of peanuts includes albumins, globulins, and glutelins.

The high biological value of peanut protein is attributed to the presence of eight essential amino acids, which the human body cannot synthesise, along with ten non-essential amino acids, making its composition comparable to animal protein (Zahran & Tawfeuk, 2019).

One approach to enhancing the nutritional value of plant proteins is the development of combined products that employ the principle of mutual protein enrichment. It is well established that plant proteins are better assimilated when combined with animal proteins. Therefore, the development of new products where animal proteins are partially or completely replaced with plant proteins, as well as the expansion of dairy product assortments incorporating plant-based ingredients with enhanced nutritional value and improved taste characteristics, is a crucial task for the dairy industry. The objective of this study was to optimise the parameters for obtaining milk-plant concentrates (MPCs) through thermos-acid coagulation of proteins in milk-plant mixtures using mathematical modeling methods and to investigate the impact of these parameters on the yield and quality characteristics of the resulting concentrates.

Materials and Methods

Method for obtaining milk-plant concentrates

The research was conducted in 2024 at the laboratories of the Department of Milk and Dairy Product Technology at the National University of Food Technologies of Ukraine. The experiment utilised skimmed milk obtained through the separation of whole milk, characterised by a total solids content of 11.5%, protein content of 3.6%, and active acidity of pH 6.5. Milk-plant mixtures (MPMs) were prepared by blending skimmed milk with a whey-plant suspension (WPS). The WPS had an active acidity of 6.7 ± 0.1 pH and a dispersed phase particle size ranging from 10 to 60 μm . To prepare the WPS, peanuts (*Arachis hypogaea*) were pre-soaked for

8-10 hours to allow for swelling, followed by washing 2-3 times. Afterward, the peanuts were mixed with rennet whey in a 1:5 ratio. The resulting mixture was homogenised for 5-7 minutes using a disperser operating at $1,000 \text{ s}^{-1}$ until a uniform consistency was achieved. The prepared WPS was filtered and added to the pre-treated skimmed milk.

The milk-plant concentrate (MPC) was obtained through thermos-acid coagulation of proteins from the milk-plant mixture. The acidity and amount of coagulant were adjusted to achieve a pH range of 5.3-5.8, corresponding to the isoelectric point of casein and the primary fractions of plant proteins. The coagulation process was carried out at a temperature of $92 \pm 2^\circ\text{C}$ by mixing the milk-plant mixture with whey, which had an acidity of $150 \pm 10^\circ\text{T}$, in ratios ranging from 1:10 to 5:10, followed by

holding for 4 ± 1 minutes. Under these conditions, the reaction medium reached the isoelectric point of the proteins, disrupting their salt bonds and forming a concentrate, which was then subjected to self-pressing. The control sample consisted of a milk-protein concentrate obtained without the addition of the whey-plant suspension.

Mathematical modeling of milk-plant concentrate quality indicators

To achieve the research objective, a full-factorial experiment (FFE) was applied. A parametric scheme for the process of obtaining milk-plant concentrates using the thermos-acid coagulation method was developed (Fig. 1), with defined input (controlling) and output (controlled) factors, as well as selected and justified optimisation criteria.

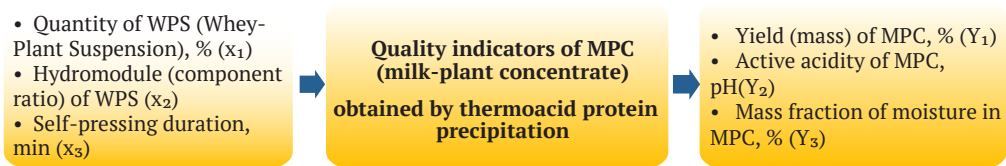


Figure 1. Parametric scheme of the process of obtaining MPC by thermoacid coagulation of milk-plant mixture proteins

Source: developed by the authors

For parameter optimisation, we determined the zero level of factors based on a priori information and the interval of their variation beyond the measurement error. The zero level corresponded to the following requirements: at these points, the optimisation parameter values were the best among all known values; the zero-level coordinates were located within the definition area. As control factors with significant impact on the qualitative indicators of milk-plant concentrates (MPC), the following were selected: x_1 – whey-plant suspension quantity, %, x_2 – hydro-module of whey-plant suspension (component ratio), x_3 – self-pressing duration, min. The output-controlled

indicators that most significantly characterise thermoacidic coagulation and influence the formation of milk-plant concentrate quality indicators are: Y_1 – yield (mass), %, Y_2 – active acidity, pH units, Y_3 – moisture mass fraction, %, Y_4 – water-retaining capacity, %. The milk-plant mixture quantity was varied from 20% to 40% with a variation step of 10%, the hydro-module of the whey-plant suspension was changed to 1:3, 1:5, 1:7, and the self-pressing duration was from 10 min to 30 min with an interval of 10 min.

During the optimisation of the MPC obtaining process by thermoacidic protein precipitation of the milk-plant mixture, the Box-Wilson

cube mathematical modeling method was used. Functional dependencies were determined by the least squares method. The method is based on determining the regression equation coefficients that provide the minimum sum of squared deviations of experimental data (Y_c) from the values calculated by the regression equation, the general form of which is presented by formula (1), where coefficients are calculated using formulas (2) and (3).

$$Y = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 + b_{12} \cdot x_1 \cdot x_2 + b_{23} \cdot x_2 \cdot x_3 + b_{13} \cdot x_1 \cdot x_3 + b_{123} \cdot x_1 \cdot x_2 \cdot x_3, \quad (1)$$

$$b_i = \frac{\sum_{u=1}^N x_{iu} \cdot y_u}{N}, \quad (2)$$

$$b_{ij} = \frac{\sum_{u=1}^N x_{iu} \cdot x_{ju} \cdot y_u}{N}, \quad (3)$$

where x_{ij} – variable value in the corresponding column of the experiment plan; y_u – result of the u -th experiment; N – total number of experiments ($N=8$); u – experiment variant number; i – factor number; j – factor number different from i .

To analyse the significance of regression equation coefficients, the adequacy of equations was determined using the Fisher criterion (F_p) according to standard methods through applied software. The selected criterion was compared with the tabular value. The equation is considered adequate under the condition of $F_p < F_m$, where F_p , F_m are the calculated and theoretical values of the Fisher criterion, respectively. Experimental conditions: $F_m = 3.050$; confidence probability – 4; number of free members $S_{\Delta HA}(f_1) = 8$; number of experiments $S_{exp}(f_2) = 5$. Experimental data were processed using the mathematical statistics method STATISTICA (StatSoft). To determine the functional dependence that most accurately reproduces the change in indicators, the approximation reliability coefficient (R^2) for each function was found. The accuracy of the obtained results is ensured by three to five-fold repetition of experiments. The results were visualised in the form

of graphs, which allowed a visual demonstration of the changes in the studied parameters.

Methods of research on the quality indicators of milk-plant concentrates

The yield (mass) was determined by the gravimetric method – the sample was weighed after self-pressing the concentrate, obtained from 1 dm³ of milk-plant mixture. Active acidity was determined potentiometrically using a Sartorius PB-20 universal pH meter (Germany). The mass fraction of moisture was measured by an accelerated method on the KVARC-21M-33 moisture meter (Ukraine), by drying the sample to a constant mass, and thermogravimetrically on laboratory electronic balance-moisture meters of the ADGS 50 series (Poland). The water-retaining capacity (WRC) of milk-vegetable concentrates was determined using the Grau-Hamm method, with A. Alekseev's modification, based on measuring the amount of water released from the product under light pressure and absorbed by filter paper.

Results and Discussion

To determine the optimal parameters for obtaining milk-plant concentrates through thermocoagulation of proteins from the milk-plant mixture, a full-factorial experiment was designed and conducted. The mathematical processing of the results allowed the formulation of analytical dependencies in the form of regression equations for calculating the impact of the amount of whey-plant suspension on the mass of skimmed milk, the hydro module (ratio of components) of the WPC, the duration of self-pressing on the yield (1), active acidity (2), mass fraction of moisture (3), and water-retaining capacity (4) of the milk-plant concentrates. For the given equations, the condition $F_p < F_T$ was satisfied, where F_p and F_T are the calculated and theoretical Fisher's criterion values, respectively, allowing us to conclude the adequacy of the obtained equations to the actual state of the process. These equations describe

the influence of three main factors: the hydromodule (x_1), the amount of whey-plant suspension (WPS) (x_2), and the duration of self-pressing (x_3) on the yield of MRC, considering their interactions and quadratic dependencies.

$$Y_{1(\text{yield})} = 13.416 - 3.1675 \cdot x_1 + 4.6236 \cdot x_2 + 2.2040 \cdot x_3 - 1.5775 \cdot x_1 \cdot x_2 - 1.0086 \cdot x_2 \cdot x_3 - 3.0879 \cdot x_1 \cdot x_3 + 5.9429 \cdot x_1^2 + 14.6335 \cdot x_2^2 + 11.7776 \cdot x_3^2, \\ B_{kpi} = 0.380; B_{kpii} = 0.978; F_r = 0.213.$$

The free term 13.416 represents the base yield level that can be expected in the absence of the influence of independent variables. The negative coefficient for x_1 (-3.1675) indicates that as the hydromodule increases, the yield decreases, since the dilution of the mixture reduces the concentration of proteins and fats, which complicates the precipitation process. The positive coefficient for x_2 (4.6236) demonstrates that an increase in the amount of CMC significantly increases the yield, as a higher amount of dry substances contributes to a higher amount of precipitate. The coefficient for x_3 (2.2040) indicates the positive effect of the duration of self-pressing, as a longer process promotes better moisture removal and higher yield. Interaction effects also play an important role. The negative coefficient for $x_1 \cdot x_2$ (-1.5775) shows that the interaction between the hydromodule and the amount of CMC reduces the efficiency of precipitation. Similarly, the negative coefficient for $x_2 \cdot x_3$ (-1.0086) suggests that an increase in the amount of CMC and the duration of self-pressing may lead to oversaturation of the system, reducing the yield. The interaction between x_1 and x_3 also has a negative impact (-3.0879), indicating the need for an optimal selection of the hydromodule and the duration of self-pressing to improve the yield. The quadratic terms reflect nonlinear dependencies. The positive coefficient for x_1^2 (5.9429) indicates that there is an optimal hydromodule value that maximises the yield. The significant positive impact

of x_2^2 (14.6335) suggests the importance of an optimal CMC level for increasing the yield. The positive coefficient for x_3^2 (11.7776) confirms the effectiveness of increasing the self-pressing duration, although within the optimal value. Therefore, the equation shows that to achieve maximum yield, it is necessary to balance the hydromodule, the amount of CMC, and the duration of self-pressing, taking into account both direct and interaction effects.

$$Y_2(\text{pH}) = 5.3902 - 1.0482 \cdot x_1 + 0.4454 \cdot x_2 + 0.7078 \cdot x_3 + 0.0725 \cdot x_1 \cdot x_2 - 0.4104 \cdot x_2 \cdot x_3 - 0.2050 \cdot x_1 \cdot x_3 + 1.2706 \cdot x_1^2 + 2.8033 \cdot x_2^2 + 1.9539 \cdot x_3^2, \\ B_{kpi} = 0.161; B_{kpii} = 0.036; B_{kpii} = 0.087; F_r = 1.107$$

The constant 5.3902 reflects the initial pH level observed in the absence of factor influences. The negative coefficient for x_1 (-1.0482) indicates that an increase in the hydromodule leads to a decrease in pH, which may be due to the lower amount of dry substances in the mixture. The positive coefficient for x_2 (0.4454) shows that as the amount of CMC increases, the active acidity rises, as plant proteins contain amino acids that affect pH. The coefficient for x_3 (0.7078) indicates a positive effect of the duration of self-pressing on acidity, which may be related to changes in protein structure and the release of substances with higher acid content. The interaction effects indicate more complex dependencies. The positive coefficient for $x_1 \cdot x_2$ (0.0725) suggests a weak positive influence of the interaction between the hydromodule and the amount of CMC. In contrast, the negative coefficients for $x_2 \cdot x_3$ (-0.4104) and $x_1 \cdot x_3$ (-0.2050) suggest that an excessive combination of CMC with the self-pressing duration or the hydromodule with the duration can lead to a decrease in acidity. The quadratic terms in the equation show nonlinear effects. The positive coefficient for x_1^2 (1.2706) indicates that there is an optimal hydromodule value to achieve higher active acidity. The significant positive

impact of x_2^2 (2.8033) confirms that the amount of CMC is an important factor affecting pH. The quadratic term x_3^2 (1.9539) also indicates that the self-pressing duration positively affects acidity within the optimal value. Overall, the equation demonstrates that active acidity is largely dependent on the amount of CMC and the duration of self-pressing, while the hydromodule has a negative impact. Interactions between factors can have both positive and negative effects, depending on their combinations. To achieve an optimal pH level, both direct and interaction effects must be taken into account.

$$Y_{3(W)} = 82.2035 - 9.2774 \cdot x_1 - 1.9996 \cdot x_2 - 0.1329 \cdot x_3 - 6.8050 \cdot x_1 \cdot x_2 - 2.1104 \cdot x_2 \cdot x_3 - 2.9817 \cdot x_1 \cdot x_3 + 13.8341 \cdot x_1^2 + 33.3881 \cdot x_2^2 + 30.1849 \cdot x_3^2, \\ B_{kpi} = 0.17; B_{kpii} = 0.202; F_r = 0.053$$

The free term 82.2035 represents the initial value of the moisture content, observed in the absence of the influence of independent variables. The negative coefficient for x_1 (-9.2774) indicates that as the hydromodule increases, the moisture content decreases. This can be explained by the fact that with an increase in the hydromodule, proteins and fats precipitate less effectively, which reduces the ability to retain water. The coefficient for x_2 (-1.9996) is also negative but smaller in value, suggesting a decrease in moisture content as the amount of CMC increases. The negative coefficient for x_3 (-0.1329) demonstrates that an increase in the duration of self-pressing slightly reduces moisture content. Interaction effects show more complex relationships. The negative coefficient for $x_1 \cdot x_2$ (-6.8050) indicates that the interaction between the hydromodule and the amount of CMC reduces moisture content, likely due to a decrease in the ability of proteins to retain water. The negative coefficient for $x_2 \cdot x_3$ (-2.1104) suggests that a combination of a higher amount of CMC and longer self-pressing reduces moisture content. A similar negative effect is observed with the interaction of $x_1 \cdot x_3$ (-2.9817). The quadratic

terms indicate the existence of optimal values for each factor. The positive coefficient for x_1^2 (13.8341) suggests that there is an optimal hydromodule value that maximises moisture retention. The significant positive coefficients for x_2^2 (33.3881) and x_3^2 (30.1849) confirm that both the amount of CMC and the duration of self-pressing are important factors for the concentrate's ability to retain moisture. Overall, the equation shows that the moisture content decreases with an increase in the hydromodule, the amount of CMC, and the duration of self-pressing. However, to achieve optimal moisture content, it is necessary to account for the interactions between factors and their quadratic effects.

$$Y_{4(WHC)} = 84.1000 - 15.0714 \cdot x_1 + 8.1691 \cdot x_2 + 8.9998 \cdot x_3 + 3.0975 \cdot x_1 \cdot x_2 - 5.8641 \cdot x_2 \cdot x_3 - 4.2857 \cdot x_1 \cdot x_3 + 18.4696 \cdot x_1^2 + 40.4773 \cdot x_2^2 + 28.0679 \cdot x_3^2, \\ B_{kpi} = 0.095; B_{kpii} = 0.191; F_r = 0.001$$

The constant 84.1000 reflects the initial moisture-holding capacity observed in the absence of the influence of independent variables. The negative coefficient for x_1 (-15.0714) indicates that as the hydromodule increases, the moisture-holding capacity significantly decreases. This may be due to the fact that a larger hydromodule reduces the concentration of proteins and fats, which contribute to water binding. The positive coefficient for x_2 (8.1691) suggests that an increase in the amount of CMC contributes to an increase in moisture-holding capacity, as plant-based proteins have high hydrophilicity. The coefficient for x_3 (8.9998) is also positive, indicating a positive effect of the duration of self-pressing on the concentrate's ability to retain moisture, as longer pressing promotes the removal of free water while retaining bound moisture. Interaction effects reflect more complex relationships. The positive coefficient for $x_1 \cdot x_2$ (3.0975) suggests that the interaction between the hydromodule and the amount of CMC partially compensates

for the negative impact of the hydromodule. In contrast, the negative coefficients for $x_2 \cdot x_3$ (-5.8641) and $x_1 \cdot x_3$ (-4.2857) indicate that a combination of a higher amount of CMC or hydromodule with the duration of self-pressing can reduce moisture holding capacity. The quadratic terms highlight the existence of optimal values for the factors. The positive coefficient for x_1^2 (18.4696) suggests that there is an optimal hydromodule level that ensures maximum moisture-holding capacity. An even greater positive impact from x_2^2 (40.4773) confirms that the amount of CMC is a key factor influencing the concentrate's ability to retain water. The positive coefficient for x_3^2 (28.0679)

indicates that the duration of self-pressing also has a significant impact within optimal values. Overall, the equation shows that to achieve a high moisture-holding capacity, it is necessary to ensure an optimal balance between the hydromodule, the amount of CMC, and the duration of self-pressing, taking into account both direct and interaction effects.

The complex changes and response surfaces of the physicochemical properties of milk-plant concentrates obtained through thermo-coagulation of milk-plant protein mixtures are presented in Figures 2 a, b, c, d as 3D graphs, reflecting the dependence of controlled parameters on controlling factors.

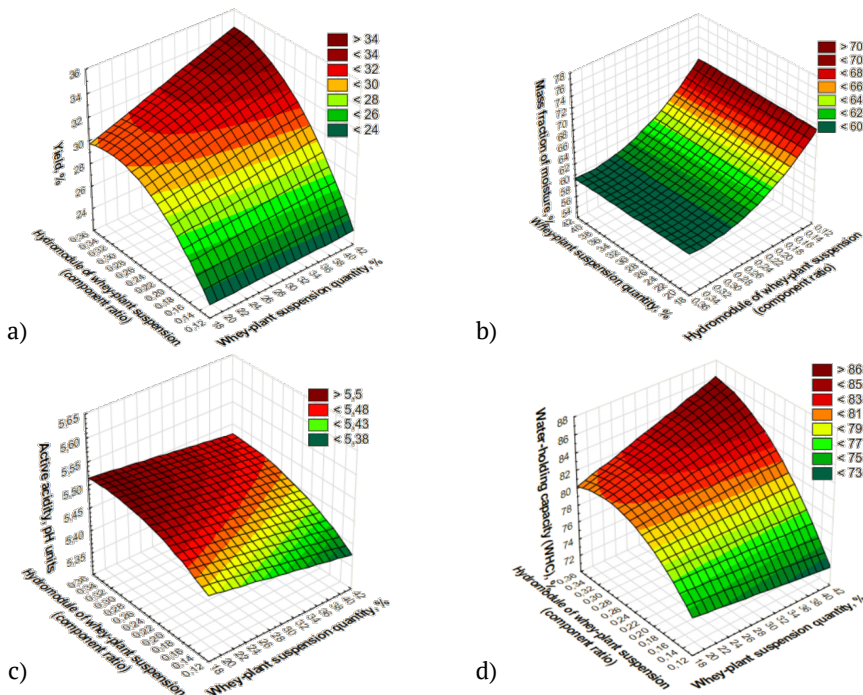


Figure 2. Response surfaces showing changes in yield (a), mass fraction of moisture (b), active acidity (c), and moisture-holding capacity (d) of milk-plant concentrates depending on the parameters of processing the milk-plant mixture

Source: developed by the authors

In the production of milk-plant concentrates (MPC), significant roles are played by the processes of structure formation and syneresis, involving protein substances. The obtained MPC

are polydisperse colloidal systems, where the dispersion medium is whey, and the dispersed phase consists of proteins and fats of both plant and animal origin. The stability of protein

globules is determined by the conformation of the particles, their charge, and the presence of a hydration shell (Lamichhane *et al.*, 2018). The concentration change of individual components of milk, as well as the type and conditions of protein precipitation, leads to a change in the nature of the bonds between protein parts.

To isolate milk and plant proteins, it is necessary to disrupt the equilibrium of at least two stability factors, which occurs during thermal denaturation. This process is accompanied by changes in the configuration, hydration, and aggregate state of the particles, which become less stable. Additionally, the degree of thermal denaturation of protein globules in milk-plant mixtures depends on temperature and heating duration (Li *et al.*, 2023). Using the proposed thermal and time regimes allows for the simultaneous coagulation of both milk proteins and plant proteins. Furthermore, as noted by authors Y. Nazarenko *et al.* (2023), the initial processing of plant proteins improves the coagulation of the milk-plant mixture, contributing to the formation of cheese curd. During the hydrolysis of soy proteins, peptides and amino acids are also formed, which create better complexes with casein micelles.

Studies have shown that during the thermocoagulation of proteins from the milk-plant mixture, increasing the amount of whey-plant suspension added to defatted milk, as well as changing its hydromodule (1:3) and increasing the duration of self-pressing, leads to an increase in the yield of MPC (Fig. 2a). This is generally characterised by an increase in the transition of both milk proteins – caseins, albumins, globulins, – and plant proteins – glutelins. The majority of fat in *Arachis hypogaea* fruits concentrates with proteins during precipitation, while the rest goes into the whey. As a result of heating the milk-plant mixtures to a temperature of 92 ± 2 °C in the presence of a coagulant (acid whey), proteins co-precipitate in a single protein complex, which also includes the fat component. The transition coefficient for the

above components during the coagulation of MPC proteins, which contains 35% whey-plant suspension with a hydromodule (component ratio) of 1:3, was about 36%. These parameters are 10-12% higher than the precipitation of proteins from the mixture of defatted milk and whey-plant suspension (20%) with hydromodules of 1:5 and 1:7.

In their studies, O. Tsisaryk *et al.* (2023) also noted an increase in the yield of the cheese product, which is related to the properties of plant proteins that facilitate the formation of structure. This ensures the formation of a dense curd and more efficient use of raw materials. The increase in cheese yield is explained by the fact that plant proteins have the ability to hold water, converting it into a bound state. This leads to their swelling, increasing mass and volume, which, in turn, increases the yield of the final product by 7-9%.

Analysing the regression equation and graphical interpretation of the change in the mass fraction of moisture in MPC (Fig. 2b), it can be concluded that increasing the amount of whey-plant suspension in the mixture from 20% to 40%, decreasing the hydromodule from 1:7 to 1:3, and the duration of self-pressing from 10 to 30 minutes, resulted in a decrease in the mass fraction of moisture in the concentrates. During the production of MPC, the hydromodule of the whey-plant suspension had almost the same effect on the final result. The maximum value of this parameter in MPC (78%) was observed when processing the milk-plant mixture containing 20% whey-plant suspension with a hydromodule of 1:7 and a self-pressing time of 10 minutes. Under the condition of processing the mixture (35% whey-plant suspension, hydromodule 1:3), the moisture in the MPC decreased by 22%. The obtained values of the mass fraction of moisture in the concentrates varied from 28.28% to 41.36% and were within the range obtained by A. Arise *et al.* (2020) in the production of a protein product from a mixture of soy and

almond milk. A. Ajayi *et al.* (2023) emphasised that the moisture content is crucial in forming the consistency and textural properties of protein products. M. Balogun *et al.* (2019) reported that a higher moisture content can promote the growth and spread of microorganisms, thus shortening the shelf life of cheese. High moisture values in cheese samples may be related to the hydrophilic nature of plant proteins.

The analysis of the effect of the variable factor space on the active acidity of MPC indicates that this parameter primarily depends on the pH of the milk-plant mixture and the coagulant: the pH decreased with a change in the hydromodule from 1:7 to 1:3 and an increase in the amount of MPC from 20% to 40%. Based on the analysis of the active acidity, a general trend was established – when increasing the amount of whey-plant suspension from 20% to 40% and changing its hydromodule from 1:7 to 1:3, the pH decreased linearly (Fig. 2c). It was found that the addition of 35% whey-plant suspension with a component ratio of 1:3 and self-pressing of the obtained concentrates for 30 minutes ensured the lowest value of active acidity of MPC at a level of 5.35. Comparing the obtained values of active acidity with the pH results of A. Ajayi *et al.* (2023), this aforementioned trend of acidity reduction with an increase in the proportion of plant milk is confirmed, and the specified results are consistently close. O. Tsisaryk *et al.* (2023) recorded that with an increase in the proportion of plant additives, a decrease in the active acidity of the product was observed: from 5.22 in the control sample to 5.11-4.96 pH units in the experimental samples. This phenomenon can be explained by the presence of a significant number of acidic amino acids in chickpea proteins.

The mathematical model describing the change in the moisture-holding capacity of MPC (Fig. 2d) shows a direct dependence of this parameter on the amount of whey-plant suspension in the milk-plant mixture and its hydromodule. The maximum value of the

moisture-holding capacity at 88% was observed in the MPC samples obtained under the highest experimental conditions – thermocoagulation of the milk-plant mixture containing 35% whey-plant suspension with a hydromodule of 1:3 and subsequent self-pressing of the curd for 30 minutes. The change in the ability of proteins to absorb ions depends on the acidity of the medium. At the point where the protein's electric charge is close to zero and the dissociation of molecules is minimal, the proteins are least able to hold water. When the pH shifts in either direction from this point, dissociation of the acidic or basic groups of the protein increases, which enhances the charge on protein molecules and, accordingly, their ability to hydrate. There is interaction between κ -casein and plant proteins (glutelins) due to the residues of N-groups and other hydrophobic bonds (Shaghaghian *et al.*, 2022).

The changes in the mass fraction of moisture and moisture-holding capacity in concentrates obtained through the thermocoagulation of proteins from the milk-plant mixture do not match the results of these parameters in the scientific development by D. Borges *et al.* (2024) and can be considered as a result of the continuous interaction between proteins, due to the reduction of the hydrated water content around casein micelles. With an increase in the amount of whey-plant suspension and changes in its hydromodule, the strength of the bonds between protein particles increases, and glutelins combine with each other and with other proteins through disulfide bonds, forming a strong three-dimensional protein network, which results in the easy release of whey contained in its interstices.

The lowest yield (22%) was observed when precipitating proteins from the milk-plant mixture containing 20% whey-plant suspension with a hydromodule (component ratio) of 1:7 and a self-pressing duration of 10 minutes. This process occurred due to the initial denaturation of plant proteins, which, when precipitating onto the surface of casein micelles,

increase their hydrophilicity, thereby reducing the degree of precipitation. The lowest value of active acidity in MPC (5.35) was obtained when processing the milk-plant mixture with 35% whey-plant suspension and a hydromodule of 1:3. The least impact on the moisture-holding capacity of MPC (72%) was observed under the following conditions: 20% whey-plant suspension with a hydromodule (1:7) and a self-pressing time of 10 minutes. Comparing the data obtained during the study with the results published by these scientists shows that the results for yield and physicochemical properties of milk-plant products, as well as the described characteristics of the technological processes used, are not contradictory and are mainly explained by differences in the plant raw materials used in the compared studies.

Conclusions

The proposed method for producing dairy-plant concentrates ensures high consumer properties and a balanced chemical composition, achieved through the optimal combination of protein components of animal and plant origin. The use of a mixture of whey and plant components in the dairy-plant mixture allows for the control of the quality of dairy-plant concentrates. This, in turn, makes it possible to expand the range of protein products by regulating moisture content, its retention, and acidity, depending on the intended use.

The conducted research showed that the most effective mixture contained 35% whey-plant suspension with a hydromodule of 1:3 and a pressing time of 30 minutes. Under these conditions, the maximum degree of protein fraction transfer into the concentrate was achieved – both dairy proteins (caseins, albumins, globulins) and plant proteins (arachin, conarachin, glutenin). The moisture retention

capacity of such a concentrate reached 76%, indicating its high functional suitability for further use in various protein products. Reducing the content of whey-plant suspension to 20% and using a hydromodule of 1:7, with a pressing time of 10 minutes, helped minimise the destabilisation of protein structures, which positively affected moisture retention in the concentrate. Under these conditions, the mass fraction of moisture reached 78%, which may be important for producing products with increased moisture, such as paste-like dairy protein desserts or alternative dairy products.

In addition to the main quality indicators, the research also confirmed the relationship between the pH level of the dairy-plant mixture and the protein coagulation processes. It was found that as the content of the whey-plant suspension increases and the hydromodule decreases, the active acidity of the concentrates gradually decreases, which can affect their organoleptic and textural characteristics. The results obtained allow for targeted regulation of the composition of dairy-plant concentrates to produce products with specified functional and technological characteristics. A promising direction for future research is the analysis of changes in quality indicators of concentrates during storage, as well as studying the effect of different temperature regimes on the stability of the protein structure and microbiological resistance.

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Conflict of Interest

None.

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Оптимізація параметрів отримання молочно-рослинних концентратів

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Анотація. Пріоритетним напрямком молокопереробної галузі є розвиток інноваційних ресурсозберігаючих технологій, які дозволяють економити сировину, збільшувати вихід та розширювати асортимент продукції. Зокрема, спостерігається тенденція до зростання попиту на рослинні аналоги молока у складі сумішей для отримання молочно-рослинних концентратів за прискореними технологіями. Метою дослідження було визначення оптимальних параметрів процесу термокислотної коагуляції білків молочно-рослинної суміші для отримання молочно-рослинних концентратів та аналіз їх впливу на вихід і якісні характеристики кінцевого продукту. Молочно-рослинні концентрати отримували термокислотним осадженням білків молочно-рослинної суміші. Для оптимізації параметрів отримання молочно-рослинних концентратів використано метод математичного моделювання – Бокса-Уільсона на кубі. Встановлено, що термокислотне осадження білків молочно-рослинної суміші, що містить 35 % сироватково-рослинної суспензії з гідромодулем 1:3 та тривалістю самопресування 30 хв., забезпечує ступінь переходу в концентрат як молочних білків, так і рослинних – на рівні 36 %. Такі параметри на 8-12 % вище, ніж осадження білків суміші зі знежиреного молока та сироватко-рослинної суспензії в кількості 20 % з гідромодулем 1:5 та 1:7. Додавання сироватко-рослинної суспензії у кількості 20 % з гідромодулем 1:7 та тривалістю самопресування згустку 10 хв.

характеризувалося найменшими процесами дестабілізації білків та максимальним значенням масової частки вологи молочно-рослинних концентратів – 78 %. В результаті аналізу активної кислотності молочно-рослинних концентратів була встановлена загальна тенденція – при збільшенні кількості сироватко-рослинної суспензії в суміші для осадження від 20 % до 40 % та зміни її гідромодуля від 1:7 до 1:3, рН лінійно знижувався. Найменший вплив на вологоутримуючу здатність концентратів (72 %) відзначено за таких умов отримання концентратів: 20 % сироватково-рослинної суспензії з гідромодулем 1:7 та тривалістю самопресування 10 хв. Отримані результати дають можливість регулювати якісні показники молочно-рослинних концентратів у залежності від подальшого їх використання для розширення асортименту білкових продуктів з регульованою масовою часткою вологи, вологоутримуючою здатністю та активною кислотністю

Ключові слова: молоко; *Arachis hypogaea*; термокислотна коагуляція; математичне моделювання; показники якості