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DEVISING A TECHNOLOGY FOR HOT THERMOSTABLE SAUCES BASED ON DAIRY RAW MATERIALS

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The object of this study is the production of hot thermostable sauces based on dairy raw materials, as well as their thermogravimetric and rheological indicators, and changes during storage.

The principal task addressed in the study is to devise industrial technology for hot thermostable sauces, which requires ensuring the stability of their structure at all stages of the technological process. The devised sauce technology involves the formation of an emulsion structure and its stabilization by introducing modified waxy corn starch and xanthan gum with subsequent pasteurization of the sauce at temperatures of 87–90°C. Comparative analysis of SEM photographs of starch before and after heat treatment confirms its thermal stability, which is manifested in the integrity of starch grains and an undamaged shell. All sauce components are integrated into a single matrix, which contributes to the stability of the final product.

The thermogravimetric and rheological indicators of the sauce and their changes during storage were investigated. During storage, there is a redistribution of the amount of free and bound water: from 39% to 36% and from 26% to 29%; the viscosity of the sauce and the shear stress increase accordingly. Sauces are structured food systems, demonstrating typical non-Newtonian behavior. The approximation of the curves of storage modulus (G′) and loss modulus (G″) at high values of angular frequency indicates the presence of cross-linked polymers.

A distinctive feature of the experimental results is that the determined thermogravimetric and rheological indicators are the basis for substantiating the shelf life of sauces. Devising a new technology could make it possible to expand the range of existing sauces and enable their industrial production. It is also the basis for the further development of the ready-to-eat segment, where sauces are a component of meals

Keywords: hot sauces, thermal stability, emulsion structure, thermogravimetric indicators, rheological indicators, storage

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1. Introduction

The food industry and restaurant businesses are trying to meet the growing demand for convenience by producing semi-finished products and ready-to-eat meals. Along with increasing convenience, their additional advantage is long-term storage. However, the development of this segment of food products is causing concern among consumers about the quality of food [1]. One of the most serious is the lack of nutrients, the use of cheap ingredients, including saturated and trans fats, refined carbohydrates, free sugars, salt, etc. Therefore, the focus of attention is on semi-finished products and ready-to-eat meals, the production technology of which provides for maximum preservation of nutritional value. This is achieved by using freezing, packaging in a modified gas environment, pasteurization, sterilization.

The food market in Ukraine and many countries of the world clearly shows a trend of increasing demand for sauces and their production in the form of semi-finished products with a high degree of readiness. The global sauces and condiments market was valued at USD 259.1 billion in 2024. It is expected to grow by 5.5% from 2025 to 2034 due to the growing desire of consumers for ease and more gastronomic pleasure [2]. In most cases, sauces are multiphase dispersed systems, mainly of the suspension and/or emulsion type, which are obtained by cold emulsification (ketchups, mayonnaises, mustard, etc.). The specified technological parameters of their production cannot be applied to the production of hot sauces. The formation of the structure of hot sauces and their further use involves repeated heat treatment. The results of such studies are important in food science as they are the basis for the development of new technologies. Given the stable growth dynamics of the market for sauces and ready-to-eat meals of industrial production utilizing them, conducting the study is a relevant and timely task.

2. Literature review and problem statement

In [3], a critical review of the most important properties of cheese sauces is given. The role of basic ingredients and additives, technologies, microbiological and sensory indicators, which is important for the food industry, is considered. It is expected that the consumption of such products would constantly increase. However, the issue of possibilities for modifying the sensory properties and nutritional value of sauces in accordance with consumer preferences remains unresolved.

In [4], the effect of heat treatment on the physicochemical properties of modified corn, potato, and tapioca starch in Alfredo sauce was investigated. It was found that in a certain range of temperatures and times, all starches demonstrated an increase in viscosity: corn – from 3328 cPs to 13296 cPs, potato – from 1200 cPs to 4656 cPs, tapioca – from 3440 cPs to 8176 cPs. It was concluded that starches have high thermal stability to the influence of technological factors and the possibility of their interchangeability. However, the issues of preserving the color of the sauce, which acquires a caramel color during heat treatment, remained unresolved. The reason is the process of melanoidin formation, which is fundamentally unacceptable.

The results in [5] report the study of sensory and rheological properties of strawberry sauces thickened with oat, potato, and corn starch mixed with xanthan gum (XG). The acquired flow curves were adapted to the rheological models of Herschel-Bulkley and Ostwald-de Weyl. It was shown that all sauces are pseudoplastic liquids, the properties of which change over time. The structure of sauces thickened with potato and corn starch is more stable during storage compared to sauces thickened with oat starch. However, the disadvantage of the work is the limited raw material of the research object as the results are relevant for strawberry sauces.

The authors of work [6] studied the influence of temperature-time parameters of thermal treatment on the viscosity of tomato sauces. In particular, the influence of temperature, duration of heating and cooling of the product was studied using four pasteurization and sterilization tests. It was shown that the reference value F (equivalent heat treatment time) is achieved using the following formulas for pasteurization (20-10-20/95 min/°C) and sterilization (20-5-20/110 min/°C or 20-5-24/110 min/°C). The determined temperature-time combinations ensure product storage at constant quality indicators and are the basis for determining safety and shelf life criteria. However, the data obtained relate to tomato sauces with a low pH value and cannot be implemented in sauces based on dairy raw materials.

In [7], information on the production and use of XG in food technology is summarized. Given its multi-vector application, the prospects for using XG in sauces and salad dressings to ensure the textural perception of products in the oral cavity are discussed. It has been shown that XG provides for the stability of the structure of sauces during freezing-thawing and heat treatment. However, the establishment of specific technological parameters (mass fraction of XG, introduction technique, temperature-time parameters of heat treatment of the recipe mixture, etc.) remains unresolved.

In [8], the use of corn starch (CS), sodium alginate (SA), or guar gum (GG) as thickeners in the technology of processed cheese sauces is discussed. It has been shown that the addition of corn starch and mixtures of sodium alginate or guar gum to processed cheese sauces has different effects on the viscosity and the value of the oil separation index. Studies of sauces by organoleptic and physicochemical indicators during 1 and 3 months of storage at temperatures of 5 ± 2°C or 25 ± 2°C confirmed their compliance with the established requirements. However, the use of individual ingredients with different contents is costly in organizational terms. An option for overcoming the difficulties may be the creation of stabilization systems for the production of sauces.

In [9], the role of XG, κ-carrageenan, guar gum, pectin, and sodium alginate in the technology of processed cheese sauces was highlighted. It was shown that all sauces, compared to control samples (without stabilizers), had slightly higher pH values and differed from each other in terms of soluble nitrogen, viscosity, and oil separation index. The highest scores during 3 months of storage were obtained for sauces with guar gum and sodium alginate. However, there are objective difficulties in using the results in sauces in the absence of cheese in their composition.

In [10], the thickening ability of four acetylated distarch adipates in a model sauce system was investigated under variations in temperature, shear, and pH. It was shown that the stability of modified starches during heat treatment decreases in the order: waxy maize starch>potato amylopectin starch>potato starch. The processing of starch granules caused clear morphological changes: swollen starch granules, subjected to strong shear, disintegrate into tiny particles. However, the issues of testing starches not in model systems but in sauces remained unresolved.

Along with the study of food additives as emulsifiers and stabilizers, the use of milk [11] and vegetable proteins [12] has attracted the attention of scientists and practitioners due to their functional and technological properties. Thus, in [11], the feasibility of using whey proteins in hot sauces based on dairy raw materials was shown. The study of microstructural and rheological parameters of sauces confirmed their resistance to the effects of two-cycle heating-cooling. However, the issue of changing the properties of sauces during storage remained unresolved, which is a deterrent to their introduction.

In [12], it is shown that the implementation of the functional and technological properties of pea aquafaba, which is a source of vegetable proteins, starch, saponins, makes it possible to obtain snack products with an emulsion structure. It is confirmed that the use of pregelatinized starch in certain concentrations and the method of introduction makes it possible to obtain stable emulsions. But the objective difficulties associated with the implementation of the technological process for obtaining pea aquafaba limit the use of the obtained results. An option to overcome this is the use of dry aquafaba, but this is quite expensive.

In [13], it is proved that in the technology of hot sauces it is advisable to ensure colloidal stability of emulsion systems in the temperature range of 1...90°C in the heating→cooling→heating cycle by implementing the functional and technological properties of the main raw material and food additives. The feasibility of using whey proteins of milk, dry fermented yolk as emulsifiers has been proven; as stabilizers – corn amylopectin and/or corn modified starch, xanthan gum, carrageenan, acidity regulators. The introduction of hot sauce technology will make it possible to offer the consumer products with high nutritional and biological value, long shelf life.

Our review of the literature [3–11, 13] demonstrates that the issues of forming the emulsion structure of hot sauces, ensuring their stability remain not fully resolved and require research.

All this gives grounds to assert that it is advisable to conduct research into the development and implementation of the technology of heat-stable sauces based on dairy raw materials. This will make it possible to bring to the market new products with a long shelf life, to improve the provision of consumers with high-quality food products.

3. The aim and objectives of the study

The aim of our research is to devise a technology for hot thermostable sauces based on dairy raw materials. This will make it possible to expand the range of existing sauces, ensure their industrial production, and will become a significant advancement for the further development of the ready-to-eat food segment, where sauces are a component of meals.

To achieve the goal, the following tasks were set:

– to construct a schematic diagram of sauce production;

– to determine the thermogravimetric and rheological parameters of freshly prepared sauces and during their storage.

4. The study materials and methods

The object of our study is the production of hot thermostable sauces based on dairy raw materials, as well as their thermogravimetric and rheological indicators, changes during storage. The principal hypothesis of the study is the possibility of industrial production of sauces, which requires ensuring their stability at all stages of the technological process. The assumptions adopted in our study regarding the possibility of using modified starches and xanthan gum as stabilizers of the emulsion structure require justification.

Assumptions accepted in the work: this study assumes that the justified composition of sauces and the parameters of individual technological operations could ensure their stability both at the production stage and during storage. It is assumed that changes in thermogravimetric and rheological indicators would make it possible to prove the stability of sauces during storage. It is predicted that changes in thermogravimetric and rheological indicators of sauces would be consistent with changes in organoleptic, physicochemical, and microbiological indicators of products.

Simplifications adopted in our work: the current study was conducted on a sauce that was produced at laboratory equipment taking into account the main parameters of emulsification, pasteurization, and degassing, which could be reproduced under industrial conditions. However, the variety of design features in production equipment may correct some of them. The study on the indicators of sauces produced under industrial conditions is not included in this paper.

Raw materials for sauce production: whey protein concentrate (manufacturer Lactelle SP., Poland), cream powder (manufacturer Roshen, Ukraine), refined deodorized sunflower oil (manufacturer TOV "SAN OIL", Ukraine). Xanthan gum (Ziboxan F-200, manufacturer Deosen Biochemical LTD, China) and modified waxy corn starch (Termflo, manufacturer Ingredion, Germany) were used as stabilizers of the emulsion structure.

Sauces were produced using a universal kitchen appliance Thermomix (Vorwerk, model TM6, Germany). The main stages of the technological process of sauce production are obtaining an emulsion system and its stabilization in the temperature range of 87–90°C, pasteurization of sauces with subsequent dosing into consumer packaging, cooling, and storage. Samples of sauces were stored in consumer packaging made of polyethylene weighing 0.2 kg. The storage temperature was 1–6°C, storage duration – 45 days, humidity – 74.5 ± 0.5%.

Analysis of samples by scanning electron microscopy (SEM) was performed using a JEOL scanning electron microscope (Japan). To prepare the samples, their surface was covered with a gold layer 50–100 Å thick by ion sputtering in a vacuum chamber with a rarefaction degree of 0.10 Pa. The area of the studied samples was 1–2 mm^2.

The study of the forms of moisture binding in product samples was carried out by the method of dynamic thermogravimetry. The temperatures of the studied sample, its mass loss, the rate of mass change and enthalpy were measured simultaneously. The study was carried out using a Q-1000 derivatograph (MOM, Hungary) in air in the temperature range of 15–800°C with a heating rate of the sample and the standard (calcined AI_2O_3) of 10°C/min.

The rheological characteristics of the studied mixtures were determined using a Kinexus Pro+ rotational rheometer (manufactured by Malvern Instruments Ltd, Great Britain). The study was carried out using the upper measuring geometry – a C25 DIN L0142 SS cylinder, and the lower measuring geometry PC25 DIN C0350. The viscosity and flow curves were acquired by changing the shear rate within the range of 0.1–100 1/s with 10 measurements per decade. Oscillatory studies were carried out at 0.5% complex shear strain in the frequency range of 10.0–0.1 Hz [14, 15]. Sauce samples were studied at a temperature of 20.0 ± 0.5°C.

The relaxation characteristics of the studied samples were determined by the dependences of shear stress and shear strain on the relaxation time over 5 minutes [16]. To approximate the obtained experimental data, the power law (1) and Herschel-Bulkley (2) models were chosen, which describe the dependence of shear stress on shear rate:

$$\tau = K \cdot \gamma^n, \quad (1)$$

$$\tau = \tau_0 + K \cdot \gamma^n, \quad (2)$$

where τ is the shear stress, Pa;

τ_0 is the shear yield strength, Pa;

γ is the shear rate, 1/s;

K is the consistency coefficient, Pa·s^n;

n is the flow behavior index.

The angular frequency ω, rad/s, or 1/s, was determined from formula (3) [17]

$$\omega = 2\pi \cdot f, \quad (3)$$

where $\pi = 3.141...$;

f is the frequency, Hz or [1/s].

The complex modulus, G^*, Pa, was determined from formula (4) [17]

$$|G^*| = \sqrt{(G')^2 + (G'')^2}, \quad (4)$$

where G' is the storage modulus, Pa;

G'' is the loss modulus, Pa.

The loss coefficient ($\tan\delta$) was determined from formula (5) [17]

$$\tan\delta = G''/G'. \quad (5)$$

The complex viscosity (η^*, Pa·s) was determined from formula (6) [17]

$$|\eta^*| = |G^*|/\omega. \quad (6)$$

Mathematical and statistical processing of the results of rheological studies was carried out using the SigmaPlot 14 and OriginPro software packages.

To assess the reliability of our results, the calculation of Student coefficients (t_{ST}) was used for the adopted level of dependence $P = 0.05$ and the corresponding (n^{-1}) number of degrees of freedom. The error in the studies was $\sigma = 3...5\%$, the number of repeated experiments was $n = 3$, the probability was $p \geq 0.95$.

5. Results of research on devising a sauce technology

5. 1. Construction of a schematic diagram of sauce production

Thermal stability (thermostability) is a critically important concept in food technology and is interpreted as the ability to resist destruction under the influence of thermal effects. In the technological process of sauce production, thermal stability must be ensured at several stages of their production. In particular, at the stage of formation of the emulsion structure of the sauce (65–75°C), its pasteurization (87–90°C), and storage (1–6°C). The schematic diagram of sauce production is shown in Fig. 1.

Devising a sauce technology that would be stable during heat treatment imposes certain requirements on their recipe composition and individual technological operations. The use of dairy raw materials, which are a source of surfactants, under intense mechanical action (emulsification) leads to aeration of the system, which is undesirable. One of the technological operations is degassing (removal of free and dissolved gases), which is carried out in the temperature range of 87–90°C.

The formation of emulsions resistant to the effects of heat treatment is ensured by the use of modified waxy corn starch and xanthan gum. Taking into account their properties (swelling, dissolution, temperature range of starch gelatinization), these hydrocolloids are introduced into the formed emulsion system at a temperature of 58–62°C with subsequent pasteurization at temperatures of 87–90°C. Fig. 2 shows SEM photographs of modified waxy corn starch grains before and after heat treatment and sauce.

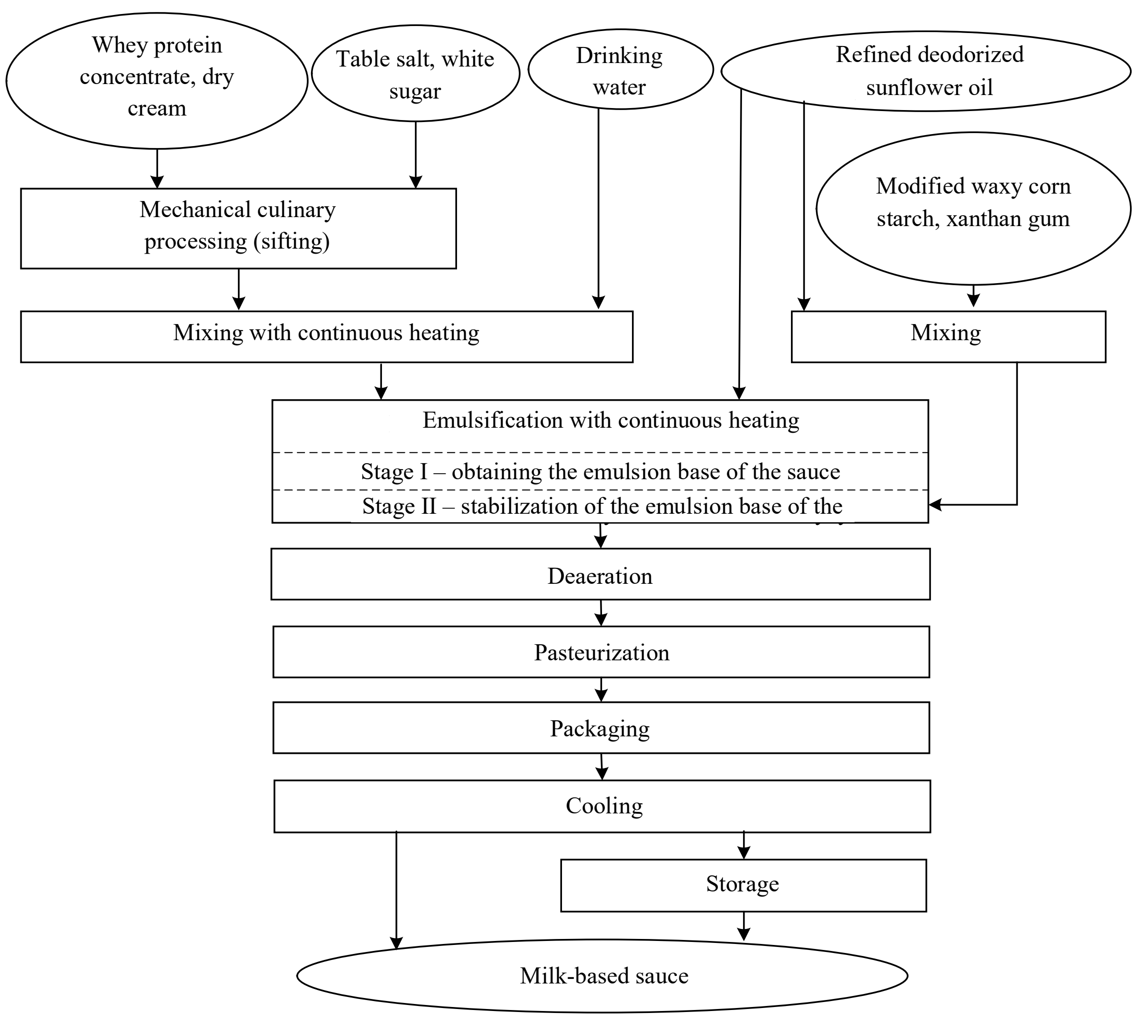
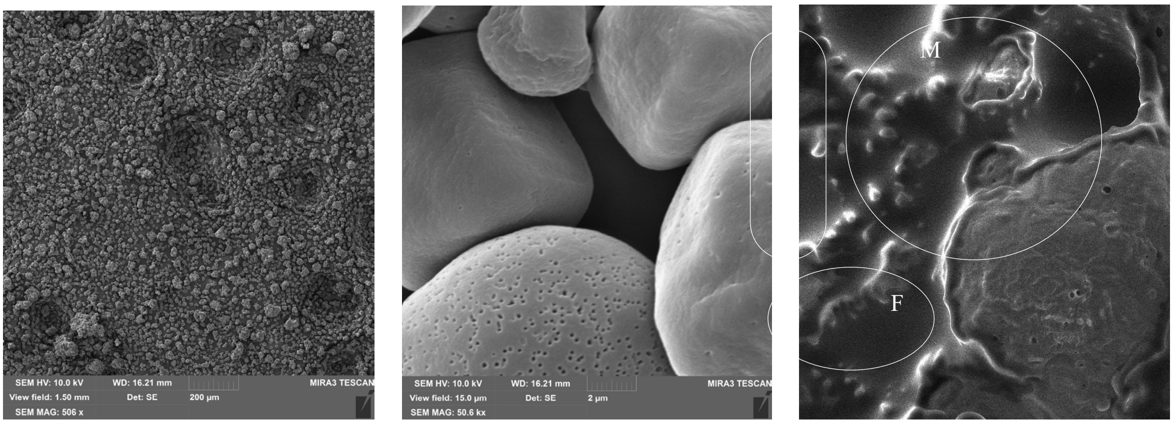


Fig. 1. Schematic diagram of sauce production



a *b* *c*

Fig. 2. SEM photographs: *a* – granules of modified waxy maize starch before heat treatment; *b* – granules of modified waxy maize starch after heat treatment; *c* – sauce (S – starch granules; F – fat globules; M – protein-polysaccharide matrix)

Photo monitoring of changes in modified waxy corn starch granules in the technological flow of sauce production allows us to draw conclusions about their role in ensuring the stability of the product's emulsion structure.

5. 2. Determining the thermogravimetric and rheological parameters of sauces during storage

One of the techniques for determining the thermal stability of food systems is the use of thermogravimetric analysis. Fig. 3, *a*, *b* shows derivatograms of freshly prepared sauces and after storage. As shown in Fig. 4, the derivatograms contain curves of the mass loss of the sample versus temperature (TG), differential thermal gravimetry (DTG, the derivative of TG curve with respect to temperature) and differential thermal analysis (DTA, the derivative of change in the temperature of the sample during heating): differential thermal analysis (DTA), differential thermogravimetric analysis (DTG), thermogravimetric (TG) curves.

Comparison of TG, DTG, and DTA profiles of freshly prepared and stored sauce samples (Fig. 3, 4) allows us to note certain features that are manifested in the position of low- and high-temperature peaks.

Fig. 5 shows dependence of the shear viscosity of freshly prepared non-degassed, freshly prepared degassed and stored sauces on shear rate under the forward and reverse modes.

Table 1 gives parameters of the constants in the mathematical equation of the Herschel-Bulkley rheological model and the power law model, which allowed us to characterize the studied samples.

Sauces are typical non-Newtonian systems, the viscosity of which depends on the shear rate. The flow behavior index ($n < 1$) indicates the pseudoplastic behavior of the studied systems. Changes in such indicators as shear stress, consistency coefficient, flow behavior index indicate changes that occur during the production and storage of the sauce.

Fig. 6 shows dependences of the storage (G') and loss (G'') moduli on angular frequency for freshly prepared non-degassed sauce, freshly prepared degassed sauce, and sauce after storage.

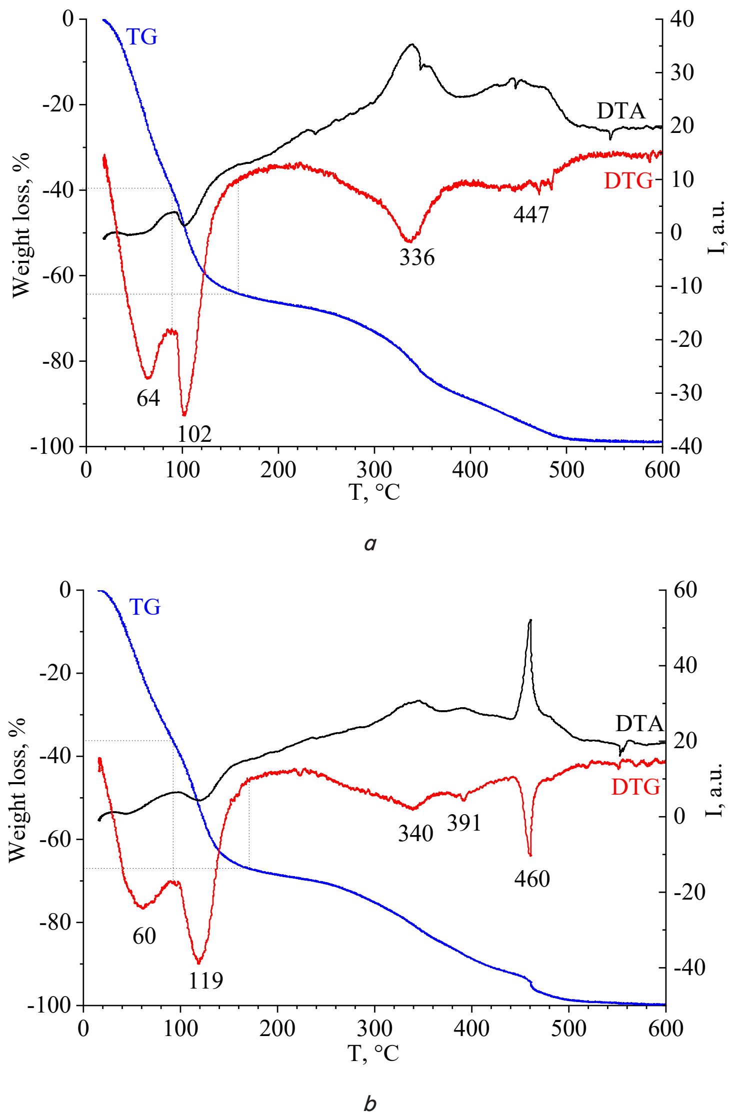
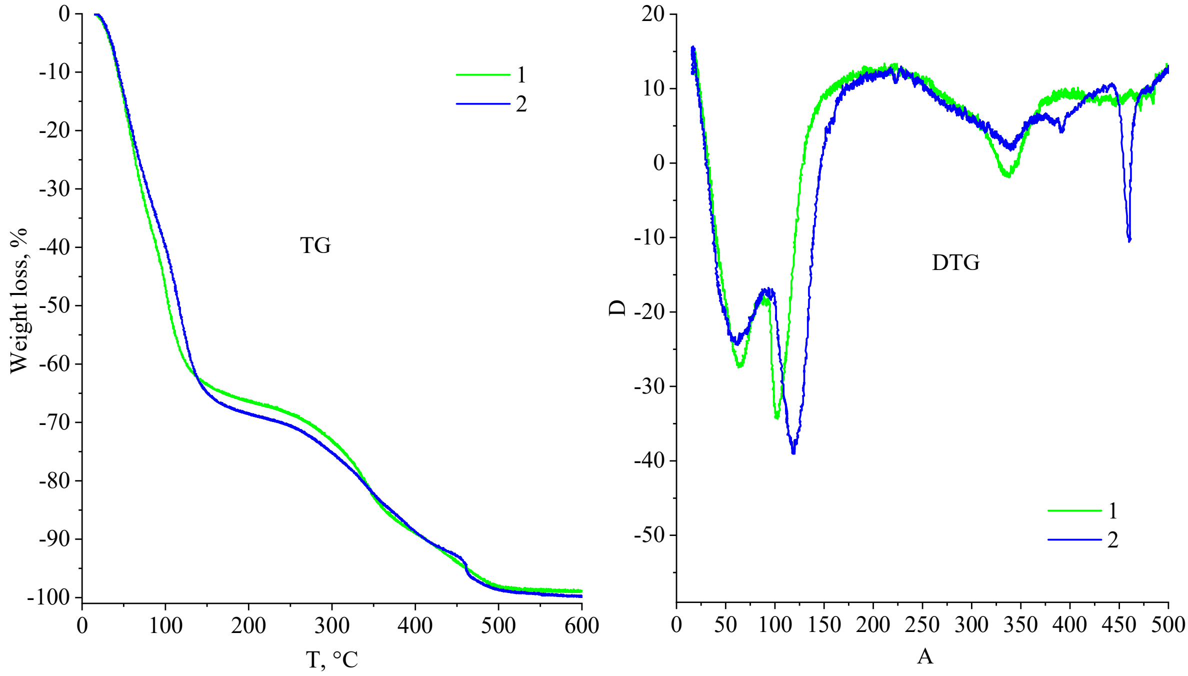


Fig. 3. Thermogravimetric studies of sauce samples: *a* – freshly prepared sauce sample; *b* – sauce sample after storage

The phase shift angle (δ) values for the studied sauce samples at low values of angular frequency (ω) are in the range of 25.1...26.0°, which indicates their similar rheological indicators. In the entire range of measurements, the phase shift angle (δ) values vary from 25.1° to 42.1°, which corresponds to $0° < \delta < 90°$ and confirms the viscoelastic behavior of the studied samples.



a *b*

Fig. 4. Dependence curves of mass loss of the sample on temperature (TG) and differential thermal gravimetry (DTG): *a* — TG curves; *b* — DTG curves; 1 — freshly prepared sauce sample; 2 — sauce sample after storage

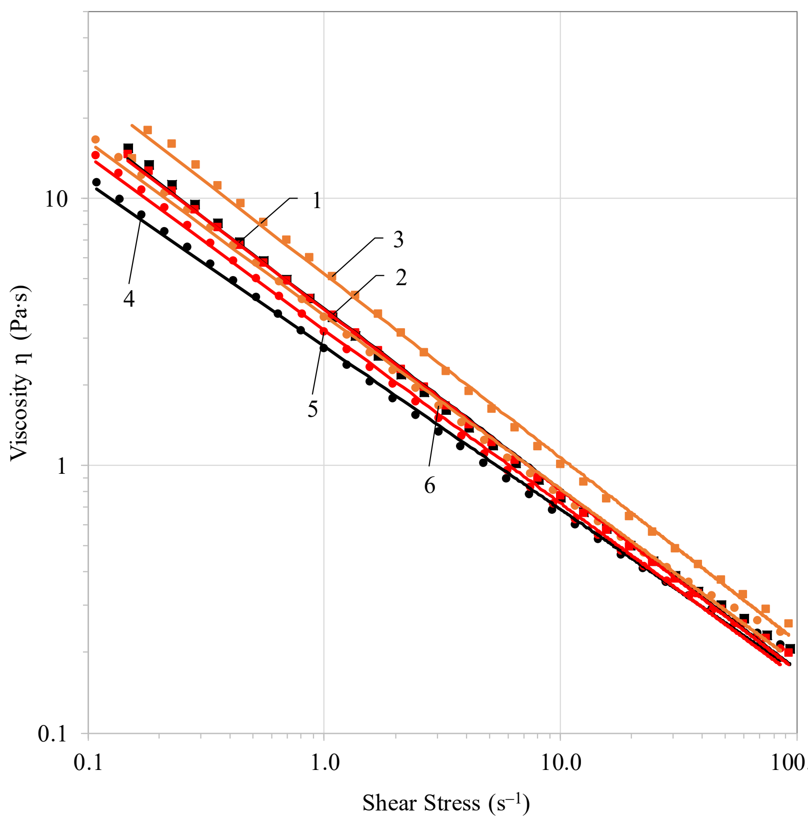


Fig. 5. Dependence of the shear viscosity of sauces on shear rate under the forward (1, 2, 3) and reverse (4, 5, 6) modes: 1, 4 — freshly prepared non-degassed sauce; 2, 5 — freshly prepared degassed sauce; 3, 6 — sauce after storage

Table 1

Parameters for fitting the dependence of shear rate and shear stress to the Herschel-Bulkley rheological model and the power law model

Indicator ID	Measurement unit	The value of sauce indicators		
		freshly made non-degassed	freshly made degassed	after storage
Herschel-Bulkley model				
Shear stress, τ_0	Pa	0.569 ± 0.100	0.579 ± 0.101	0.782 ± 0.152
Coefficient of consistency, K	Pa·s^n	3.094 ± 0.083	3.195 ± 0.106	3.722 ± 0.157
Flow behavior index, *n*	–	0.349 ± 0.012	0.369 ± 0.016	0.364 ± 0.018
Correlation coefficient, R^2	–	0.9999	0.9999	0.9999
Standard error, SE	–	0.0381	0.0490	0.0597
Power law model				
Coefficient of consistency, K	Pa·s^n	3.796 ± 0.017	3.791 ± 0.018	4.514 ± 0.023
Flow behavior index, *n*	–	0.269 ± 0.003	0.298 ± 0.004	0.296 ± 0.004
Correlation coefficient, R^2	–	0.9998	0.9997	0.9998
Standard error, SE	–	0.0532	0.0695	0.0792

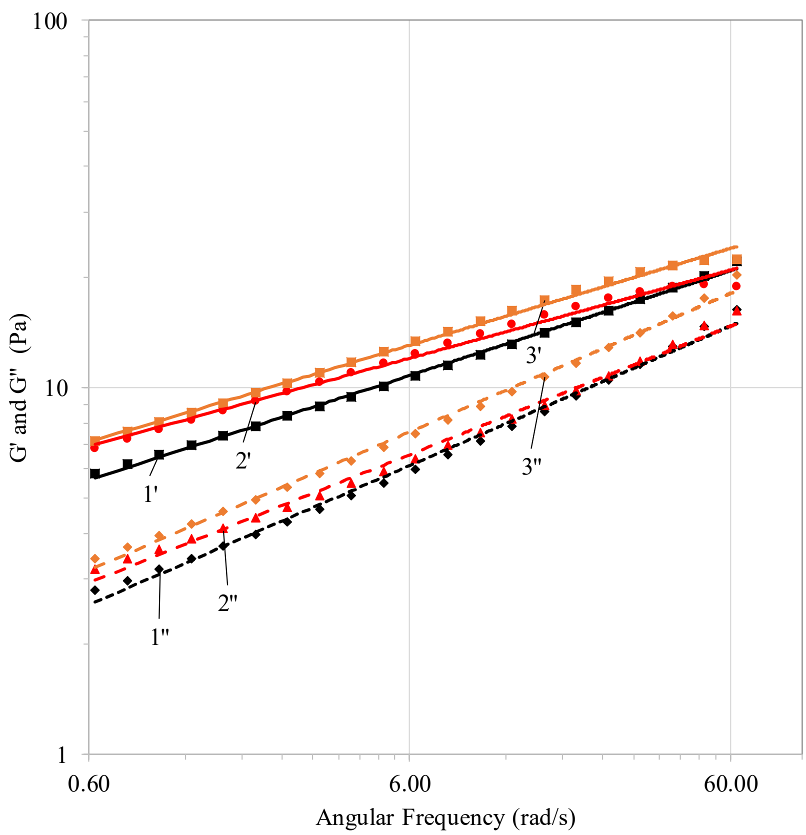


Fig. 6. Dependence of the storage modulus (G') and loss modulus (G'') of sauce samples on angular frequency [ω, rad/s]: 1', 1'' — freshly made sauce, not degassed; 2', 2'' — freshly made sauce, degassed; 3', 3'' — sauce after storage

The storage (G') and loss (G'') moduli are approximated using a power law model, the linear regression correlation coefficients (R^2) are above 0.98, which confirms the adequacy of the selected model. The resulting parameter values are summarized in Table 2.

The obtained parameters confirm the similarity of the studied samples to each other; however, the increase in the values of consistency coefficients K' and K'' reflects the increase in the viscous and elastic properties of the samples during storage.

Table 2

Power law model parameters designed for frequency response curves of the studied sauces

Sample ID	G'			G''		
	K', Pa·sn'	n'	R^2	K'', Pa·sn''	n''	R^2
Freshly made sauce, not degassed	6.4606	0.2854	0.9973	3.0994	0.3801	0.9927
Freshly made sauce, degassed	7.8068	0.2402	0.9810	3.5067	0.3497	0.9918
Freshly made sauce after storage	8.1101	0.2642	0.9910	3.8461	0.3775	0.9928

6. Discussion of results related to devising a sauce technology

In [18], the conditions and terms of storage of sauces were substantiated by determining their organoleptic, physicochemical, and microbiological indicators after storage for 45 days. In contrast to [11], our studies highlight the features of sauce technology in relation to their thermogravimetric and rheological indicators, including after storage.

The technological process of sauce production (Fig. 1) involves the phased implementation of the following operations: mechanical culinary processing of raw materials, heating of the recipe mixture with subsequent emulsification of oil, introduction of starch and xanthan gum, degassing. The following stages include pasteurization at a temperature of 87–90°C, cooling to a temperature of 1–6°C, and storage at a temperature of 1–6°C.

To justify the choice of starch and determine its role in stabilizing the emulsion structure, SEM photographs were taken before and after heat treatment (Fig. 2, *a*, *b*). It was found that starch granules have a characteristic polyhedral shape, and the morphology of starch granules is uniform in size. Thermal treatment of starch suspensions with subsequent pasteurization at temperatures of 87–90°C leads to water absorption and starch gelatinization. Under these conditions, the size of the granules increases, and they acquire an elliptical shape (Fig. 2, *b*). A noticeable difference is that visible pores and small surface folds appeared on the surface of the starch granules. All starch granules after heat treatment retained their integrity and had an intact shell, which is a confirmation of their thermal stability.

Fig. 2, *c* shows an SEM photograph of the sauce, which indicates its heterogeneous structure. The SEM photograph shows starch granules (designation *S*), which are included in the protein-polysaccharide matrix (*M*), pores-shells, which contain fat globules (*F*). The starch granules in the sauce have an oval shape, the surface of the starch granules with surface folds is covered with a protein-polysaccharide layer. All components of the sauce are integrated into a single matrix, which contributes to the stability of the final product.

The study of thermogravimetric indicators of sauces (Fig. 3, 4) showed the following. The DTG curves of the samples contain two peaks in the region from 20.0 ± 0.5°C to ≈ 150°C, which are accompanied by endothermic effects (peaks directed downwards) on the DTA curves. The presence of such peaks reflects the course of a two-stage process of water removal from the samples. In this case, the peak at a temperature of 60–64°C characterizes the removal of unbound water. Note that the peak at a higher temperature (102–119°C) characterizes the removal of bound water (such as that which forms hydrogen bonds with –OH, –COOH, –NH– or other hydrophilic groups of molecules of the organic component of the sample). The total amount of water in the sample during storage does not change significantly (65 ± 1%, Fig. 3, *a*), however, there is a redistribution of the amount of free and bound water: from 39% to 36% and from 26% to 29%, respectively. In addition, the position of the higher-temperature maximum of water removal shifts from 102°C to 119°C (Fig. 3, *b*). The above changes in the derivatograms can be interpreted as a slight increase in the proportion of bound water in the samples during their storage. The reason for this increase may be the formation of hydrogen bonds between hydrophilic groups of proteins and polysaccharides with water molecules.

In addition to the water removal peaks, higher-temperature peaks are observed in the derivatograms on the DTG curve, each of which is accompanied by an exothermic peak on the DTA curve (Fig. 4). Such peaks characterize the processes of decomposition and combustion of the organic component, which for the sample before and after storage begins at a temperature of about 200°C. At the same time, the high-temperature profile of the DTG and DTA curves is somewhat different. Thus, the content of dry matter (more precisely, the organic combustible component) during storage does not change significantly and is 35 ± 1% (Fig. 3, *a*). The completeness of combustion of the sample after storage does not significantly increase from 98.8 to 99.9.

The position of the low-temperature peak of the primary decomposition of the organic component shifts slightly from 336°C to 340°C (Fig. 4, *b*), but its intensity decreases almost by half after storage of the sample. Instead, a new, higher-temperature exothermic peak appears for the sample after storage at a temperature of 391°C. A wide asymmetric exothermic peak with a maximum of about 447°C transforms after storage of the product into a clear narrow exothermic peak in the temperature range of 460°C. These changes are also reflected in the TG curve (Fig. 4, *a*) and are manifested in the redistribution of the amount of the organic component that decomposes (burns in the presence of oxygen) at different stages (in different temperature intervals).

Analyzing the set of data according to the results of thermal analysis, we can make assumptions about the reason for the differences observed for samples of freshly prepared sauce and after storage. Storage for 45 days leads to an increase in the content of bound water, a clearer separation of exothermic peaks on the DTG and DTA curves and a shift of their position to the high-temperature region. Such changes may be due to the high hydration capacity of xanthan gum and milk proteins. However, to confirm or deny the possibility of such processes, additional studies using other physicochemical methods are necessary.

The study of the viscosity of sauces under the forward and reverse modes is illustrated in Fig. 5. The viscosity curves in logarithmic coordinates have a linear relationship for three samples, demonstrating typical non-Newtonian behavior. The technological operation of degassing (Fig. 1) is aimed at removing the air phase of the sauce and is important for ensuring its quality and safety indicators. Degassed products are physically and chemically more stable and have a longer shelf life. From the data in Table 1, it is clear that degassing contributes to an increase in the shear stress, consistency coefficient, and flow behavior index. This is quite natural, since the removal of the air phase leads to the formation of a denser, unbroken dispersion medium and, as a result, an increase in its stability. The increase in the consistency coefficient of the sauce after storage (Table 1) indicates an increase in viscosity. This is also confirmed by the increase in shear stress, which indicates the need to apply a greater force to deform the sauce after storage compared to a freshly prepared sample.

Along with viscosity, an important rheological indicator is the storage modulus, which characterizes the elastic properties of sauces at small deformations (Fig. 6). It is worth noting that for the sauce after storage at the maximum angular frequency (62.8 rad/s), a convergence of the curves of the storage modulus (*G*’) and the loss modulus (*G*’’) is observed. In this case, the phase angle of the shift (δ) is equal to 42.1°, and the tangent of the loss angle (tan *δ*) is 0.91, which is as close as possible to the reference values of δ=45° and tan δ=1. This indicates that at this measurement point an almost equal ratio of the elastic and viscous components of the studied samples is observed. The approximation of the curves to the storage modulus (*G'*) and loss modulus (*G''*) at high values of angular frequency may indicate the presence of crosslinked polymers in the samples under study.

The gel-like nature of the studied samples is indicated by the values of the tangent of the loss angle (tan δ), which do not exceed unity (tan δ<1). However, taking into account the values of the tangent of the loss angle (tan δ) (0.48–0.74 – freshly prepared sauce not degassed, 0.47–0.86 – freshly prepared sauce degassed, 0.48–0.91 – sauce after storage), it can be concluded that the system at rest exhibits the properties of a weak gel. With an increase in the angular frequency (ω), the sauces demonstrate behavior characteristic of pseudoplastic systems. The studied sample of non-degassed sauce is also characterized by the dominance of the values of the storage modulus (*G'*) over the loss modulus (*G''*) in the entire measurement range (Fig. 6).

The slopes of the curves *G'* and *G''* confirm that the sauces have the properties of weak gels. This is consistent with the desired textural properties: when dosing or applying to the surface of food products, the sauce will behave as a fluid, viscous. When at rest on the surface of the food product, it will demonstrate gel-like properties, due to which it will not drain.

Summarizing our experimental data, it should be noted that the sauce samples belong to viscoelastic gels since the accumulation modulus curve (*G'*) prevails over the loss modulus curve (*G''*). The obtained experimental data of the frequency sweep of the sauce samples (Table 2) are approximated using a power law model. The determined linear regression correlation coefficients (R^2) above 0.98 indicate the adequacy of the use of this model.

The limitation of this work is that the rheological parameters of sauces were investigated at a temperature of 20.0 ± 0.5°C. This does not fully characterize the properties of sauces since the consumption of sauces in ready-made meals is carried out at temperatures of 65–75°C. In addition, samples of sauces produced under laboratory conditions may differ slightly from those produced under industrial conditions. This is a drawback of the study since the use of production technological equipment can affect, first of all, the stability of the sauce and its rheological parameters.

The determination of thermogravimetric and rheological parameters was carried out for a basic sauce based on dairy raw materials. Our study in the future involves the development and determination of quality and safety indicators, justification of conditions and warranty period of storage of derivative sauces with fillers of plant and animal origin.

7. Conclusions

1. A technological scheme for hot thermostable sauces based on dairy raw materials has been devised, which involves the formation of an emulsion structure and its stabilization by introducing modified waxy corn starch and xanthan gum with subsequent pasteurization of the sauce at temperatures of 87–90°C. The feasibility of degassing the recipe mixture at the pasteurization stage has been proven, as a result of which the sauces are physically and chemically more stable and have a long shelf life. A comparative analysis of SEM photographs of starch before and after heat treatment confirms its thermostability, which is manifested in the integrity of starch grains and an undamaged shell. SEM photographs of the sauce allow us to draw conclusions about the heterogeneity of its structure. All components of the sauce are integrated into a single matrix, which contributes to the stability of the final product.

2. Thermogravimetric and rheological indicators of the sauce and their changes during storage have been investigated. The presence of peaks on the DTG curves reflects the course of a two-stage process of water removal from the samples – unbound at a temperature of 60–65°C and bound at a temperature of 102–119°C. During storage, a redistribution of the amount of free and bound water occurs. The reason for this may be the formation of hydrogen bonds between hydrophilic groups of proteins and polysaccharides with water molecules.

The viscosity curves of sauces in logarithmic coordinates have a linear dependence for all samples, demonstrating typical non-Newtonian behavior. Storage affects the rheological parameters of sauces – viscosity and shear stress increase. The approximation of the curves to the storage modulus (*G'*) and loss modulus (*G''*) at high values of angular frequency (62.8 rad/s) may indicate the presence of cross-linked polymers. The slopes of the *G'* and *G'* curves confirm that the sauces exhibit the properties of weakly structured gels. This is consistent with the desired textural properties: when the sauce is used in prepared meals, it will behave as a fluid, viscous, non-draining sauce.

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

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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