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DEVELOPMENT OF TECHNOLOGY FOR FOOD PRODUCTS WITH EMULSION STRUCTURE BASED ON PEA GROATS AND PEA AQUAFABA

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The object of this study is a vegetable appetizer, as well as its sensory, physicochemical, microbiological, rheological, microstructural indicators, and their changes after 30 days of storage.

The main task addressed within the framework of the study was the implementation of both pea groats (the basic raw material) and pea aquafaba (an intermediate semi-finished product) in one technological flow of food production. This approach contributes to the rational use of resources, the implementation of scientifically based parameters of the technological process, and the practical implementation of sustainable development concepts through the valorization of intermediate semi-finished products.

A model of the recipe composition and a schematic diagram of food products with an emulsion structure based on pea groats and pea aquafaba have been developed. It has been experimentally determined that the developed products are characterized by high sensory indicators that remain stable during storage. The mass fraction of dry matter in the studied samples was 45.1 %, the mass fraction of protein was 4.3 %, and the carbohydrates were 13.6 %. The water activity in freshly prepared appetizers was 0.910, and after 30 days of storage, it was 0.902. Rheological and microstructural indicators confirmed the formation of a stable multicomponent structure.

A distinctive feature of the experimental results is that the emulsion structure of the developed food product is provided with the technological properties of aquafaba.

The technological solutions proposed in this work aim to make food products that meet the growing demand for plant-based, functional, and economically affordable products. The practical implementation of the devised technology could contribute to meeting consumer demands and introducing innovative trends in the development of the food industry, through resource efficiency of production processes

Keywords: pea groats, aquafaba, vegetable appetizers, emulsion structure, rheological indicators, microstructure

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1. Introduction

The shift in focus from local to global problems of humanity contributes not only to finding ways to rationally use resources but also to valorizing intermediate semi-finished products formed during food production.

Peas as a food crop are an affordable source of vegetable protein, have agroecological, biological, and technological advantages compared to other types of legumes. Peas are high-yielding crops that can adapt to various climatic growing conditions, and owing to the process of symbiotic nitrogen fixation, enrich the soil with nitrogen. In the technological flow, peas can be used in full: from whole grain to products of their processing, such as textured flour, protein concentrates, extrudates. Pea grains, pea groats are recognized as an inexpensive, easily accessible source of protein, complex carbohydrates, vitamins, and minerals. High nutritional value, relatively low starch digestibility, low glycemic index define peas as a valuable food resource for the food industry. Therefore, it is relevant to develop food products from pea groats by implementing an integrated approach to its processing. The result of such an approach will be, on the one hand, the use of pea groats as a source of vital macro- and micronutrients, on the other hand, the implementation of the technological properties of pea aquafaba as an intermediate semi-finished product will ensure the formation of an emulsion structure of the product.

2. Literature review and problem statement

The technological properties of peas are studied in the context of their nutrient composition, including the high content of protein, starch, fiber, and trace elements, which is implemented in the production of protein isolates, starch, flour, extrudates.

In work [1], the creation of emulsion systems based on pea protein, which is obtained mainly by precipitation, was highlighted. It was found that the methods of processing peas and protein extraction have a significant impact on the emulsifying properties of proteins, and not the type of oils or the method of obtaining emulsions. The disadvantage of this technology is the formation of a significant number of by-products, for which it is necessary to find ways to use them.

In work [2], the use of native pea flour, which contains 50 % starch and 20 % protein, is proposed to create stable emulsions. The authors' attention is focused mainly on comparing the functional properties of emulsions based on pea flour and concentrated pea protein. However, the possibilities of using pea flour for stabilizing emulsions are limited by the oil content up to 10 %.

In [3], the use of pea flour for the production of appetizers by extrusion processing and nitrogen as a physical foaming agent was proposed. The use of nitrogen makes it possible to vary the physical, textural, and microstructural properties of extrudates. This method expands the potential for the sale of legumes in the food industry, but the issue of the high cost of the technology, the variability of the search for optimal technical parameters, and possible losses of nutrients present in peas remains open.

In the food industry, the technological potential of peas remains under-utilized, as only its individual fractions are mainly used to obtain protein isolates, flour, starch, and extrudates. Such a narrowly focused approach limits the possibility of comprehensive use of pea seeds and groats as food raw materials capable of ensuring the creation of food products with specified properties. Comprehensive implementation of the technological potential of peas could contribute to the production of innovative products that meet modern consumer demands and the principles of sustainable development.

The implementation of sustainable production principles in the technological flow of legume processing remains a pressing issue, in particular, due to the formation of related semi-finished products and the need to find effective methods for their valorization. One of such semi-finished products is aquafaba, which is formed during the hydrothermal processing of legumes. The use of aquafaba is becoming relevant due to the growing interest in its emulsifying, foaming, thickening, and gelling properties.

In most published works, scientists' attention is focused mainly on the study of aquafaba. This approach contributes to the search for its further uses.

In [4], a modification of green pea aquafaba was proposed using ultrasonic treatment. Ultrasound improves the technological properties of aquafaba, namely the foaming and emulsifying ability, the stability of foams and emulsions. However, the question of implementing this technology on an industrial scale remains, as well as the economic feasibility of the process, taking into account energy consumption and the complexity of the equipment.

In [5], the possibility of using aquafaba from chickpeas, beans, yellow split peas, and green lentils in the meringue technology was investigated. It was found that aquafaba from green lentils has the highest foaming ability, and aquafaba from chickpeas and peas demonstrates the highest organoleptic indicators. However, optimization of technological parameters is necessary to ensure reproducibility of results in industrial conditions.

In [6], the emulsifying properties of aquafaba canned from chickpeas or peas were used in the technology of vegetarian mayonnaise. The product developed by the authors had similar organoleptic and rheological characteristics to an analogous egg-based product. However, the work used aquafaba from canned legumes, which casts doubt on the possibility of implementing the technology on an industrial scale.

Aquafaba as an object of research is attracting increasing attention from scientists. However, analysis of the literature and patent databases reveals the absence of food product technologies that simultaneously realize the technological potential of both boiled peas and the resulting aquafaba. Despite separate studies on the technological properties of aquafaba, no such solutions have been identified, which emphasizes the need to devise such a technology.

In [7], the process of accumulation of dry matter in aquafaba obtained under different parameters of hydrothermal processing of legumes, including peas, was investigated. However, the limited experimental data is due to the lack of proposed practical ways of using the obtained semi-finished products.

Our review of the literature [1–7] allows us to state that the development of food product technology based on pea groats and pea aquafaba is relevant. Given the stable dynamics of the average annual growth of the appetizer market, due to the growing demand for plant-based and ecological products, this segment of goods was chosen to implement the technological properties of peas and aquafaba. Such a choice makes it possible to combine innovation, functionality, and compliance with modern trends in the food industry.

3. The aim and objectives of the study

The purpose of our study is to devise a technology for vegetable appetizers with an emulsion structure based on pea groats and pea aquafaba (hereinafter referred to as vegetable appetizers). This will meet modern requirements for ecological and healthy food products, integrating innovative approaches and principles of sustainable production. This approach will contribute to the development of the agro-industrial sector, ensuring high product quality, its environmental safety, and competitiveness.

To achieve the goal, the following tasks were set:

– to build a model of the recipe composition and a schematic diagram of the production of vegetable appetizers;

– to determine the sensory, physicochemical, and microbiological indicators of a vegetable appetizer freshly prepared and after 30 days of storage;

– to investigate the rheological and microstructural indicators of a vegetable appetizer freshly prepared and after 30 days of storage.

4. The study materials and methods

The object of our study is a vegetable appetizer, as well as its sensory, physicochemical, microbiological, rheological, and microstructural indicators, as well as their changes during storage.

The main hypothesis of the study assumes the possibility of involving both pea groats (the main raw material) and pea aquafaba (an intermediate semi-finished product), which was previously subject to disposal, in the technological flow of appetizer production. The implementation of this technology makes it possible to make a product with new consumer properties that meets the principles of responsible consumption and production.

Basic assumption is that the technological properties of aquafaba could enable the formation of emulsions that would contribute to the formation of the desired sensory indicators of the final product, in particular, provide a stable emulsion structure.

The starting materials for the study were split pea groats (variety "Motto", growing region – Odesa Oblast), pregelatinized starch chemically modified purified from waxy corn (Ultra-Tex 2131, manufacturer – Ingredion). The raw materials used met the requirements of acting regulatory documents.

Samples of vegetable appetizers were prepared using the universal kitchen equipment Thermomix (Vorwerk, model TM6, Germany). The studied samples of vegetable appetizers were stored at a temperature of 1–6 °C for 30 days. The appetizers were packed in a weight of 200 g in plastic containers made of polymeric material.

Physical-chemical indicators were determined by generally accepted standard methods. The mass fraction of dry substances was determined by drying at a temperature of 103±2 °C to constant mass, protein – by the Kjeldahl method (the conversion factor of total nitrogen to protein is 6.25). Fat was determined by the Soxhlet method, starch – by the polarimetric method, carbohydrates – by the liquid chromatography method. Ash was determined by burning a portion of the sample in a muffle furnace (calcination at a temperature of 550±25 °C).

The particle size of the samples was measured using laser diffraction on a PSA 1190 particle size analyzer in the range of 0.1–2500 μm. The samples were diluted in water (~30 °C) at a ratio of 1/100 to prevent possible multiple scattering effects. The prepared sample was added in portions to the measuring cell to obtain the required degree of filling of the field of view. All measurements were performed at a stirrer speed of 150 rpm to 450 rpm [8]. The particle size in the volume average diameter $D_{4,3}$ was determined from the following formula [9]:

$$D_{4,3}=\frac{\sum_{i}^{n}D^{4}iVi}{\sum_{i}^{n}D^{3}iVi}. \quad (1)$$

The SPAN index was calculated using the formula [9]:

$$\mathrm{SPAN}=(D_{90}-D_{10})/D_{50}, \quad (2)$$

where D_{10} is the particle diameter at 10 % of the total size distribution, respectively;

D_{50} is the particle diameter at 50 % of the total size distribution, respectively;

D_{90} is the particle diameter at 90 % of the total size distribution, respectively.

The rheological characteristics of the samples were determined on a Kinexus pro+ rotational rheometer. For the studies, the upper geometry in the form of a round plate with a diameter of 40 mm (PU40 SR5040 SS:PL61 ST) was used, which was fixed on a vertical shaft. The samples were placed on the lower platform, after which the shaft with the plate was lowered to a gap of 1 mm. The viscosity and flow curves were obtained by changing the shear rate in the range of 0.1–100 1/s with 10 measurements per decade. Oscillatory studies were carried out at 0–100 % of the complex shear strain in the frequency range of 0–10 Hz [10, 11].

The relaxation characteristics of the studied samples were determined by the dependences of the shear stress and shear strain on the relaxation time for 5 minutes [12]. To approximate our acquired experimental data, the power law and Herschel-Bulkley rheological models were chosen. The power law model was mathematically described using the formula:

$$\tau=K\cdot\gamma^{n}. \quad (3)$$

The Herschel-Bulkley rheological model was mathematically described using the formula [13]:

$$\tau=\tau_{0}+K\cdot\gamma^{n}, \quad (4)$$

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.

Angular frequency ω [rad/s] or [1/s] was determined from the following formula [14]:

$$\omega=2\pi\cdot f, \quad (5)$$

where π=3.141…

f – frefuency, Hz or 1/s.

Complex modulus, G^*, Pa, was determined from the following formula [14]:

$$|G^*|=\sqrt{(G')^2+(G'')^2}, \quad (6)$$

where G' is the storage modulus, Pa;

G'' is the loss modulus, Pa.

The loss factor or damping factor tanδ, was determined from the following formula [14]:

$$\tan\delta=G''/G'. \quad (7)$$

The complex viscosity, η*, Pa·s, was determined from the following formula [14]:

$$|\eta^*|=|G^*|/\omega. \quad (8)$$

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

Water activity was determined on a Rotronic HygroLab-2 water activity analyzer (Rotronic, Switzerland) at a temperature of 20±1 °C in the measurement range of 0…1 a_w (0…100 % relative humidity). The studied sample of vegetable appetizer was taken into a container and placed in a measuring chamber. Measurements were carried out in accordance with DSTU ISO 21807:2007.

Emulsion stability was determined in accordance with DSTU 4560:2006.

Analysis of samples by electron microscopy was performed using a Jeol scanning electron microscope (Japan).

The key information indicator of this method is the signal generated as a result of the interaction of the flow of charged particles with the surface of the sample under study. To prepare the samples, their surface was covered with a layer of gold 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.

Microbiological indicators were determined as follows: QMAFAnM – according to DSTU 8446:2015, *L. Monocytogenes* MV 10.10.2.2.-132-2006, BGKP – GOST 30518-97, pathogenic microorganisms including *Salmonella* bacteria – DSTU EN 12824:2004, molds and yeasts – DSTU 8447:2015, *S. Aureus* – GOST 10444.2-94.

The organoleptic characteristics of the analyzed samples were assessed using an expert evaluation method. Sensory indicators of vegetable appetizers were determined by the profile method (sensory profile), which makes it possible to determine the descriptors of sensory indicators and the intensity of expression in the form of a profilogram.

Sensory indicators of the appetizer are divided into descriptors, the intensity of which is estimated on a 5-point scale: 5 – very strong intensity; 4 – strong intensity; 3 – moderate intensity; 2 – weak intensity; 1 – the feature is barely noticeable; 0 – the feature is absent.

The specified method of sensory evaluation of a vegetable appetizer corresponds to a simplified approach since it does not involve comparing the taste range of samples and does not include a control sample due to the absence of an analog product.

To assess the reliability of our results, the calculation of Student coefficients (t_{ST}) was used for the adopted dependence level P=0.05 and the corresponding (n^{-1}) number of degrees of freedom.

5. Results of devising food technology based on pea groats and pea aquafaba

5. 1. Construction of a model of the recipe composition and a schematic diagram of vegetable appetizer production

The content of the main recipe components, which is represented in the form of a model of the recipe composition (Table 1), the technological parameters of individual technological operations (Table 2), and the schematic diagram of vegetable appetizer production (Fig. 1) were experimentally substantiated.

Table 1

Model of the recipe composition for a vegetable appetizer

Raw material name	Mass fraction of components, %
Split boiled pea groats	24...26
Pumpkin and/or carrots, boiled, chopped	24...26
Pea aquafaba	21...23
Refined deodorized sunflower oil	25...26
Pregelatinized starch	1...2
Mixtures of spices, flavoring additives	2...4

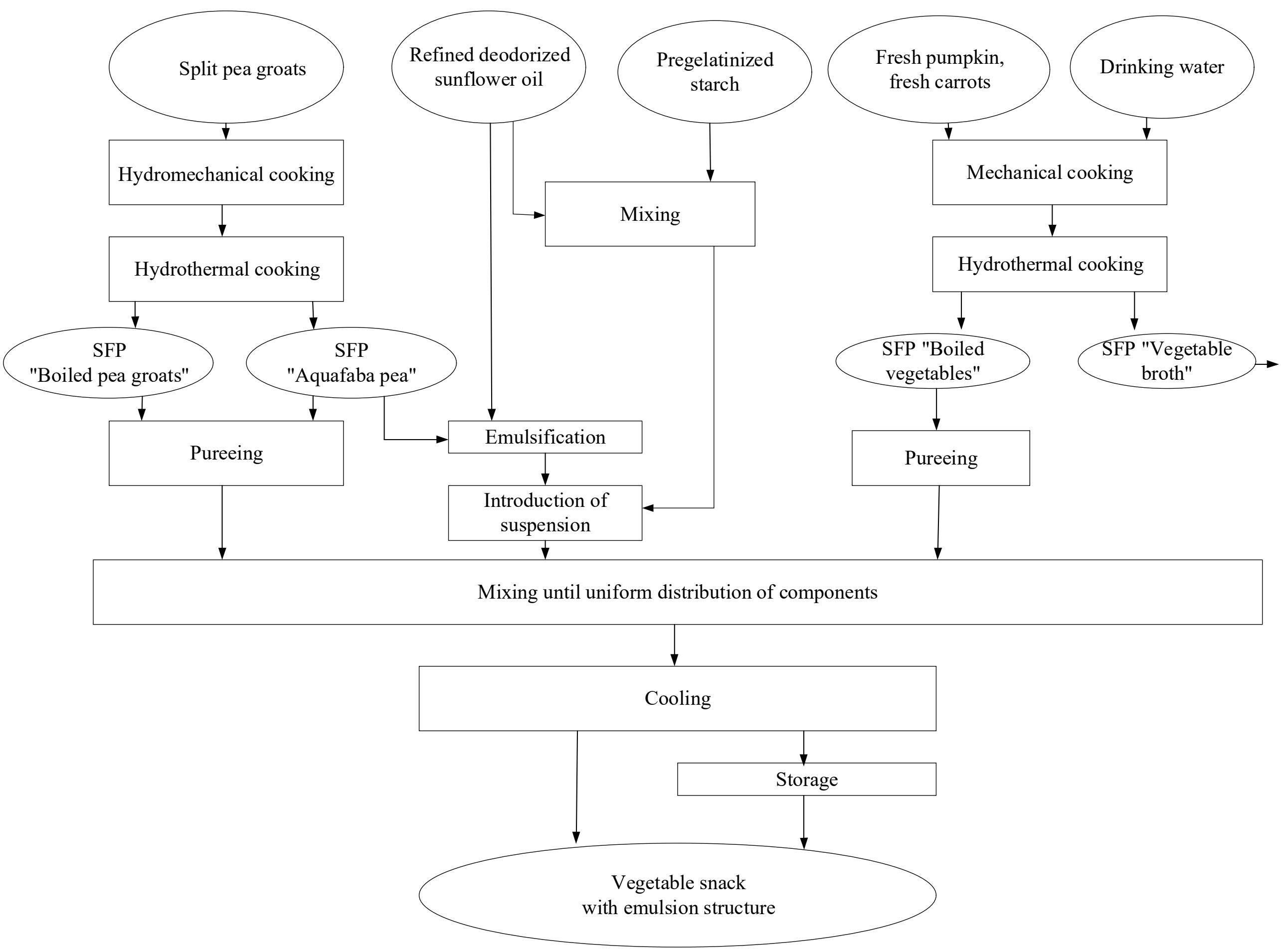

Fig. 1. Schematic diagram of vegetable appetizer production

The technological process of vegetable appetizer production involves obtaining intermediate semi-finished products "boiled crushed mountain groats", "boiled crushed pumpkin and/or carrots", "emulsion system based on aquafaba", their step-by-step connection with subsequent packaging and packing.

During the technological process, split pea groats were sorted, washed, and soaked in drinking water at a temperature of 18±0.5 °C for 4.0...4.5 h at a hydro module of 1:2.5. Cooking of rehydrated groats was carried out using the basic method (99±1 °C). The groats were poured with drinking water in a ratio of 1:1.5 and cooked for 50...60 min. After hydrothermal treatment, legumes were crushed with the addition of 10...20 % aquafaba to form a homogeneous, smeary texture. The remainder of aquafaba was used to obtain an emulsion system based on it.

Fresh food pumpkin, fresh carrots were sorted, cleaned, cooked in the basic way at a hydro module of 1:3, and then ground to a puree-like homogeneous mass.

The semi-finished product "aquafaba-based emulsion system" was obtained in two stages. First, the oil was dispersed in aquafaba at a speed of 3000 rpm for 0.5 min. Then, a mixture of oil and starch (in a ratio of 1:10) was gradually introduced and dispersed for 3.5 minutes to stabilize the resulting system.

The determined rational parameters for obtaining vegetable appetizers make it possible to take into account various factors of the technological process, which will ensure high sensory indicators and consumer appeal of appetizers.

5. 2. Determination of sensory, physicochemical, and microbiological indicators of vegetable appetizers freshly prepared and after 30 days of storage

Profilograms of sensory evaluation of vegetable appetizers, freshly prepared and after 30 days of storage, are shown in Fig. 2.

The most important sensory indicators of vegetable appetizers are taste and consistency, which determine the overall acceptability of the product for the consumer and are critical in identifying defects in the finished product. The study of sensory indicators of vegetable appetizers, freshly prepared and after 30 days of storage, showed that compared to the control sample, there is a slight decrease in odor intensity.

Results of investigating the physicochemical indicators of vegetable appetizers are given in Table 3.

Table 3

Physical-chemical indicators of vegetable appetizers, freshly prepared and after 30 days of storage (n=5, $P \geq 0.95$)

Name of the indicator	Vegetable appetizer, freshly prepared	Vegetable appetizer, after 30 days of storage
Mass fraction of dry matter, %	45.1	44.8
Mass fraction of protein, %	4.3	4.3
Mass fraction of fat, %	25.9	25.8
Mass fraction of total carbohydrates, %:	13.6	13.4
Starch, %	7.2	7.1
Sugars, %	3.2	3.1
Fiber, %	3.2	3.2
Mass fraction of ash, %	1.3	1.3
Water activity	0.910	0.902

Table 2

Rational parameters for obtaining a vegetable appetizer

Parameter ID	Units	Cut-off values	Process control points
Hydromechanical processing of pea groats			
Duration	h	4.0–4.5	–
Drinking water temperature	°C	18±0.5	
Ratio of pea groats:drinking water	w/w	1:2.5	
Hydrothermal treatment and grinding of pea groats			
Duration	min	50–60	Mass fraction of solids in aquafaba, W=4.6–4.8 %. Average diameter of pea particles $D_{4,3}$=127.1–138.0 μm
Temperature	°C	99±1	
Ratio of pea groats:drinking water	w/w	1:1.5	
Hydrothermal treatment and chopping of vegetables (fresh food pumpkin, fresh carrots)			
Duration	min	20–30	Average diameter of vegetable particles $D_{4,3}$=179.7–232.0 μm
Temperature	°C	99±1	
Ratio vegetables:drinking water	w/w	1:3	
Obtaining an emulsion based on pea aquafaba			
Emulsification temperature	°C	18–22	Average size of the fat phase in the product $D_{4,3}$=13.71–16.85 μm. Viscosity η=1.23–1.59 Pa·s, at γ=40.0 1/s. Emulsion stability 98–99 %
Mass fraction of emulsion stabilizer (pregelatinized starch)	%	1–2	
Rotation speed of the emulsifier working body	rpm	3000	
Emulsification duration	min	4.0	
Obtaining the finished product – vegetable appetizer			
Rotation speed	rpm	1500	Viscosity η=7.91–8.52 Pa·s, at γ=40.0 1/s. Emulsion stability 98–99 %
Duration of mixing of semi-finished products "Chopped boiled pea groats", "Chopped boiled vegetables", "Emulsion based on pea aquafaba"	min	3.5–5.0	
Cooling	°C	4 – 6	
Storage			
Temperature	°C	1 – 6	Viscosity η=8.01–8.43 Pa·s, at γ=40.0 1/s. Emulsion stability 98–99 %
Humidity	%	75	
Warranty period	24 h	30	

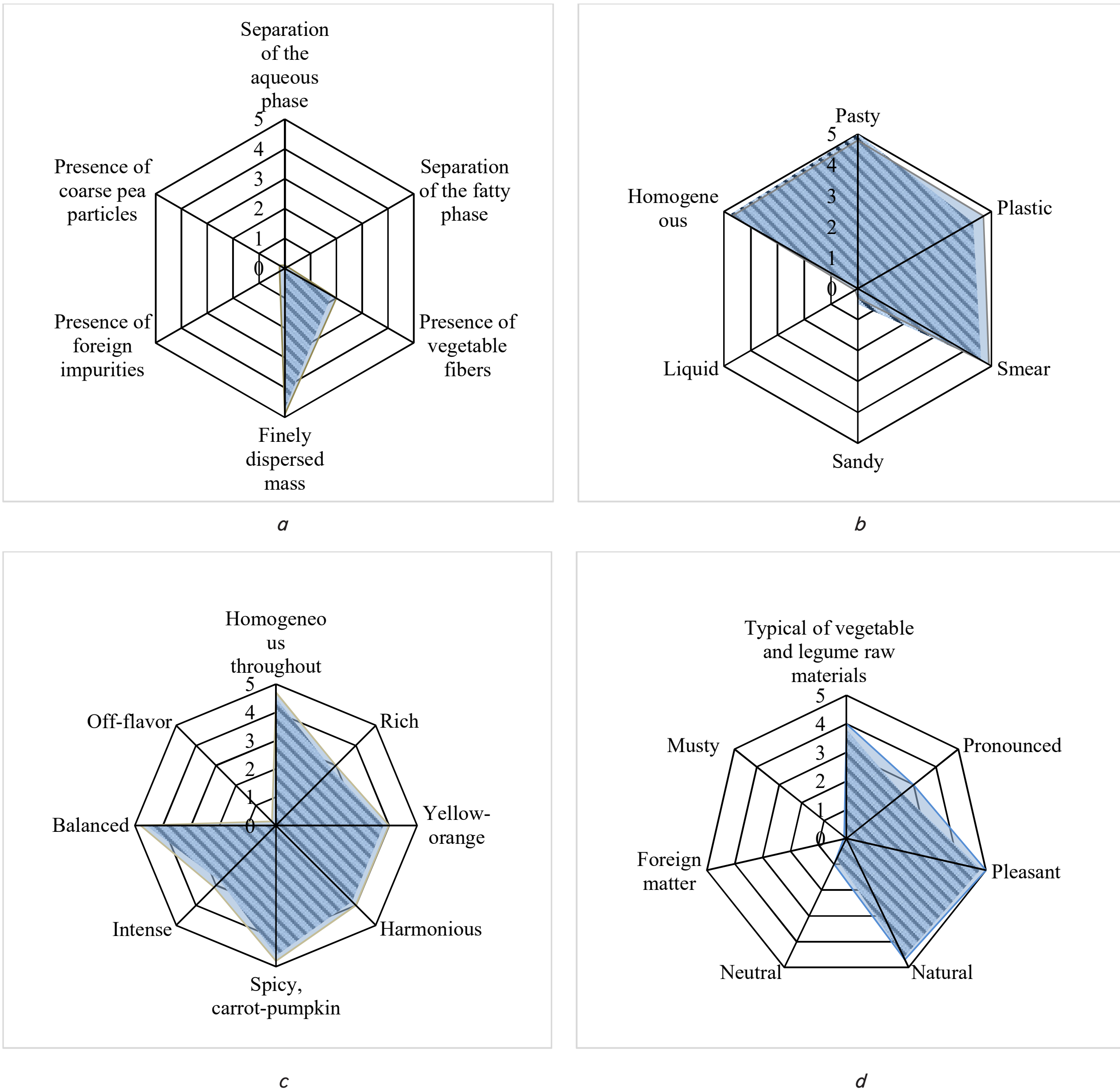

Fig. 2. Organoleptic profile of vegetable appetizer: *a* – appearance and consistency; *b* – texture; *c* – color, taste; *d* – smell; ■ – freshly prepared vegetable appetizer; ■ – appetizer after 30 days of storage

Experimental data allowed us to establish that the mass fraction of dry matter in appetizers is 45.1 %, the mass fraction of protein is 4.3 %, carbohydrates – 13.6 %, in particular fiber – 3.2 %, ash – 1.3 %. During storage, the physical and chemical indicators of the products remain stable.

The water activity indicator was determined as one of the methods for predicting the duration of storage. This indicator reflects the microbiological, physical, and chemical stability of the product. Considering that a certain value of water activity corresponds to specific types of microorganisms capable of developing under these conditions, the microbiological indicators of vegetable appetizers were studied (Table 4).

Based on experimental data, the storage period of the developed vegetable appetizer was determined and justified – 30 days at a temperature of 1–6 °C and a relative humidity of no more than 75 %.

Table 4

Microbiological indicators of vegetable appetizers (n=5, P≥0.95)

Indicator ID	Permissible levels	Characteristics	
		Vegetable appetizer, freshly prepared	Vegetable appetizer, after 30 days of storage
L. monocytogenes in 25.0 g	Not allowed	Not detected	Not detected
Pathogenic microorganisms, including *Salmonella* bacteria in 25.0 g	Not allowed	Not detected	Not detected
Staphylococcus aureus S. Aureus in 1.0 g	Not allowed	Not detected	Not detected
Escherichia coli bacteria in 0.01 g	Not allowed	Not detected	Not detected
Molds and yeasts, CFU/g	$1\cdot10^6$	<10	$<10^2$
Mesophilic aerobic and facultative anaerobic microorganisms, CFU/g	1×10^2	2,0·10	6,0·10

5. 3. Study of rheological and microstructural parameters of freshly prepared vegetable appetizer and after 30 days of storage

Fig. 3 shows a dependence of the shear viscosity of vegetable appetizers on shear rate in the forward and reverse direction. The studied samples demonstrate the typical behavior of a non-Newtonian fluid, which is characterized by a decrease in effective viscosity with increasing shear rate (pseudoplastic behavior).

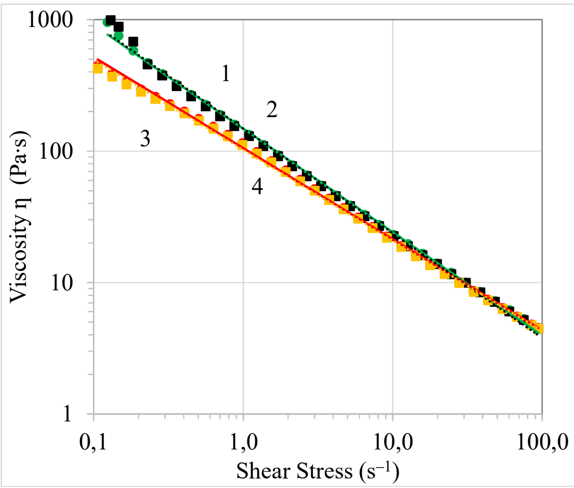

Fig. 3. Dependence of shear viscosity (η, Pa·s) of vegetable appetizers on shear rate (γ, s^{-1}) under the forward (1, 2) and reverse (3, 4) modes, where: 1, 3 – freshly prepared; 2, 4 – after 30 days of storage

Results of the frequency sweep of the studied appetizer samples are shown in Fig. 4.

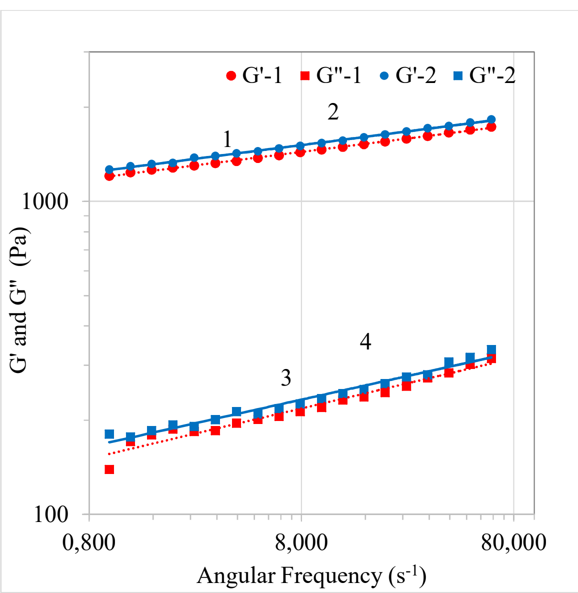

Fig. 4. Dependence of the modulus of elasticity (G', 1, 2, Pa) and the modulus of viscosity (G'', 3, 4, Pa) of vegetable appetizers on angular frequency (ω, rad/s), where: 1, 3 – freshly prepared; 2, 4 – after 30 days of storage

Frequency sweep studies of appetizer samples (Fig. 4) make it possible to determine their physical stability at rest throughout the entire storage period, determining whether destabilization processes will occur during this period. The storage modulus (G') describes the proportion of elastic properties and corresponds to the part of the energy that is stored. The loss modulus (G'') corresponds to the viscous properties and determines the part of the energy that is lost during sinusoidal deformation [15].

The frequency sweep study of the samples shows that in the entire range of angular frequency measurements, the obtained values of the elastic modulus G' exceed the values of the viscous modulus G'', since $G' > G''$, which indicates the predominance of elastic properties over viscous ones.

The values of G^*/G' increase with increasing values of the angular frequency (ω), while the values of the complex viscosity (η*) decrease. This can be explained by the increase in the stiffness of the samples.

The modulus of viscosity G'' in the vegetable appetizer sample after 30 days of storage compared to the freshly prepared one has a slight tendency to increase, which indicates that the texture of the appetizers is stable during storage. The modulus of elasticity G' and viscosity G'' are fitted to a power model; the correlation coefficients of linear regression (R^2) are above 0.97, which confirms the adequacy of the use of the selected model. The resulting parameter values are summarized in Table 5.

Table 5

Parameters of power-law models designed for frequency sweep curves of the studied samples

Name of samples	G'			G''		
	K', Pa·$s^{n'}$	n′	R^2	K'', Pa·$s^{n''}$	n''	R^2
Appetizer, freshly prepared	1,203.5	0.0859	0.9983	156.19	0.1606	0.9731
Appetizer, after 30 days of storage	1,260.9	0.0877	0.998	170.1	0.1507	0.975

Based on the experimental data, the results were fitted to the Herschel-Bulkley rheological model, which is summarized in Table 6.

Table 6

Herschel-Bulkley model parameters

Indicator name	Unit of measurement	The value of indicators for a vegetable appetizer	
		Freshly made	After 30 days of storage
Yield shear stress, τ_0	Pa	45.2±4.6	49.9±5.1
Consistency coefficient, K	Pa·s^n	96.7±4.8	88.0±5.3
Flow behavior index, n	dimensionless	0.301±0.016	0.235±0.021
Correlation coefficient, R^2	–	0.9999	0.9999
Standard error, SE	–	0.988	1.308

The characteristics of constants in the mathematical equation of the Herschel-Bulkley rheological model allowed us to characterize the studied samples. According to the description of the flow curves [13], the ultimate shear stress of the freshly prepared appetizer and after 30-day storage is 45.2 and 49.9 *Pa* ($\tau_0>0$), the flow behavior index is 0.301 and 0.235 ($n<1$), the consistency coefficient is 96.7 and 88.0 (K>0). The rheological properties of the vegetable appetizer reflect certain sensory indicators that are important for the perception by the end consumer. One of the key semi-finished products that affects these indicators is the emulsion, which is part of the appetizer as an intermediate semi-finished product. Taking into account the influence of the emulsion on the properties of the final product, its microstructure was investigated (Fig. 5).

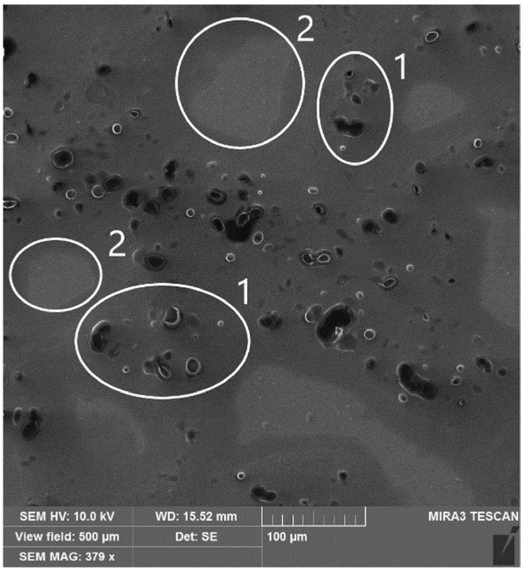

Fig. 5. Scanning electron micrographs of emulsions based on pea aquafaba: 1 – swollen granules of pregelatinized starch; 2 – fat droplets

Scanning electron micrographs of the emulsion (Fig. 5) allowed us to assess the particle distribution, emulsion stability, and determine the effectiveness of the selected stabilizer.

For a comprehensive assessment of the properties of the developed product, the microstructure of the appetizer was investigated (Fig. 6).

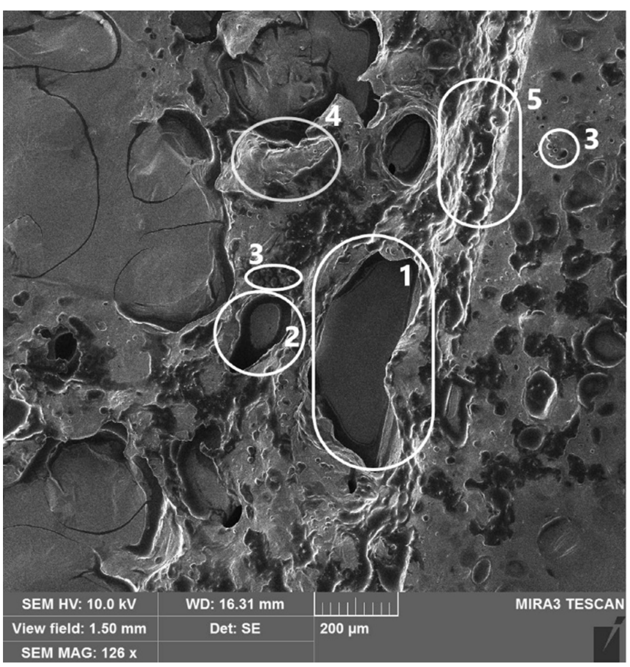

Fig. 6. Scanning electron micrographs of a vegetable appetizer: 1 – air bubbles; 2 – fat globules; 3 – swollen starch grains; 4 – pieces of crushed peas; 5 – pumpkin and carrot fibers

Microstructural analysis allowed us to visualize the internal organization of the components and determine the role of each component in shaping the properties of the product.

6. Discussion of results based on substantiating the technology of vegetable appetizers

The idea of devising the technology of food products was implemented within the framework of the technology of vegetable appetizers (Fig. 1). The use of selected raw materials (Tables 1, 2) makes it possible to achieve high nutritional value and sensory indicators while simultaneously achieving the principles of sustainable production.

In works [1–3], the proposed technologies are expensive and focus on obtaining a specific semi-finished product, transforming others into surplus ones that require disposal or additional technological solutions for their implementation. Unlike [1–3], our technology is focused on the comprehensive implementation of the technological properties of the formed semi-finished products within the framework of a single technology of food products.

The appetizer was a plastic, pasty mass with a homogeneous consistency. The color of the product was characterized by harmony and uniformity throughout the mass. The smell is moderately pronounced, carrot-pumpkin, pleasant, without foreign odors. The taste is defined as balanced and harmonious. Accordingly, the developed vegetable appetizer is characterized by high sensory indicators (Fig. 2), which will contribute to a positive perception of the innovative product by consumers.

The developed product after 30 days of storage demonstrated a high level of stability of the specified sensory indicators compared to the control freshly-prepared sample. The plasticity and uniformity of the texture, harmonious and uniform color, typical smell, as well as balanced taste were preserved. This indicates the effectiveness of the selected technological solutions.

Water activity (Table 3) in the studied vegetable appetizer samples corresponds to the value of 0.910. This indicates that the appetizers are prone/sensitive to the risk of microbiological spoilage. Accordingly, the appetizer technology provides for the use of potassium sorbate. Requirements for storage, transportation and are set out in the developed TU 10.8-44234755-002:2024 "Appetizers based on legume raw materials".

The appetizer technology involves the use of pregelatinized starch as a stabilizer of the emulsion structure. In addition to stabilization, starch granules bind moisture in the product and form a desired consistency by swelling. This contributes to emulsion stability and reduces the risk of microbiological contamination.

The decrease in the water activity value of the appetizer from 0.910 to 0.902 during storage may be due to the process of additional swelling of the starch granules, as a result of which they absorb free liquid present in the product.

Based on the study of microbiological indicators of vegetable appetizers (Table 4), it was found that the number of mesophilic aerobic and facultative anaerobic microorganisms, mold fungi, and yeast in the product is at a level that does not exceed the permissible norms. Bacteria of the *E. coli* group, pathogenic microorganisms (including *salmonella* bacteria), *S. Aureus*, *L. monocytogenes* were not detected in the appetizer, which confirms the safety of the product.

When characterizing the rheological indicators of the product, it should be noted that the forward and reverse curves (Fig. 3) do not coincide. This indicates the presence of thixotropic behavior in all studied appetizer samples. However, in the range of low shear rates (from 1 to 0.1 1/s), the systems are not fully restored, regardless of the type of the studied sample – freshly prepared or after 30 days of storage. Using the area under the curves calculation method, it was determined that the structure recovery of the studied freshly prepared appetizer is 86.78 %, and after storage – 86.44 %.

Measurements of rheological properties (Fig. 4) of the studied samples at high values of angular frequency (ω) make it possible to characterize the behavior of the samples under short-term deformation effects, and at low values of angular frequency (ω) under long-term static deformation effects. Accordingly, the obtained data make it possible to characterize the rheological parameters of the studied samples under various technological effects (packaging, storage). At low values of angular frequency (ω), the tangent of the loss angle (tan δ) varied within the range of 0.11–0.15. With an increase in angular frequency, an increase in tan δ values up to 0.18 was observed, which is characteristic of both freshly prepared samples and samples after storage. The determined values of tangential loss ($\tan\delta<1$) indicate that the appetizers are structured systems. The constancy of the values of tangential loss tanδ both in the freshly prepared appetizer and after 30 days of storage indicates a high structural stability of the product, which confirms the preservation of its organoleptic properties during storage (Fig. 2).

Phase shift angle (δ) in the entire measurement range (Fig. 5) does not exceed 10.4°, which indicates the viscoelastic behavior of the studied samples, because with this behavior, values (δ) in the range $0°<\delta<90°$ are characteristic. The obtained experimental data (Fig. 4) make it possible to state that the studied samples are characterized by the dominance of elastic properties over viscous ones with physical stability. This will guarantee the preservation of the sensory indicators of the vegetable appetizer, both freshly prepared and after 30 days of storage, without losing its properties during transportation and sale.

The statistical analysis (Table 5) confirmed an insignificant change in the rheological properties of the studied samples, freshly prepared and after 30 days of storage, where the average values of the determined parameters are in the same range. The values of the elastic moduli (*G*') and viscosity (*G*'') in the specified range of angular frequency (ω) in the first and after 30 days of appetizer storage did not change significantly.

Based on the determined characteristics in the Herschel-Bulkley equation constants (Table 6), the studied appetizer samples can be characterized as nonlinear-plastic. An increase in the ultimate shear stress τ_0 from 45.2 to 49.9 may indicate an increase in the structuring of the appetizer samples (compaction of the internal matrix or simply compaction of the structure). At the same time, a decrease in the consistency coefficient from 96.7 Pa·s^n to 88.0 Pa·s^n and a decrease in the flow behavior index from 0.301 to 0.235 indicate that the product becomes less viscous and fluid.

Scanning electron micrographs of the emulsion (Fig. 5) demonstrate that the fat droplets have clear boundaries, their distribution in the system is relatively uniform, which indicates their stability. Starch granules in the emulsion system are characterized by an uneven and somewhat rounded shape, with a diameter in the range of 10–40 μm. The surface of the starch particles is heterogeneous, with dark zones and deep cavities, which indicates partial water absorption and structural reorganization. Scanning electron micrographs (Fig. 5) show the formation of a dense spatial distribution of starch, which forms a structure that mechanically holds the dispersed phase. The introduced starch partially absorbs liquid, forms a physical barrier around the fat droplets and simultaneously increases the viscosity of the system, which indicates the effectiveness of using pregelatinized starch to stabilize the formed emulsion systems based on aquafaba.

Scanning electron micrographs of the vegetable appetizer (Fig. 6) indicate its heterogeneous, complex, and multicomponent texture. All components of the appetizer are integrated into a single matrix, which contributes to the stability of the final product, providing the desired emulsion structure and organoleptic indicators. Thus, in the central part of the micrographs, large pores similar to air bubbles are visible, which are formed during emulsification and combining of all recipe components, which provides a light texture when consuming the appetizer. Darker areas in the form of drops correspond to fat globules, which are evenly distributed in the product matrix. Next to the fat globules are swollen starch granules that bind the available liquid. Heterogeneous areas with a slightly porous surface with visually different densities correspond to fragments of crushed peas and vegetables – pumpkin and carrot.

The developed food production technology ensures the comprehensive use of the technological potential of peas and the resulting aquafaba, contributing to the implementation of sustainable production principles in the food industry.

The experimental data obtained have certain limitations due to the biological and varietal characteristics of the raw materials used, as well as the technical characteristics of the equipment used. In view of this, the work identifies control points of the technological process that ensure the reproducibility of sensory, physicochemical, and microbiological indicators of vegetable appetizers.

The limitation of our work is the use of a specific type of raw material in the technology, the change of which can affect the organoleptic, rheological, microbiological, physicochemical indicators of the formed semi-finished products and the final product. The prospect of further research is to expand the range of vegetable appetizers based on other types of legumes and vegetables, shifting attention from food products containing sources of animal proteins to vegetable ones.

7. Conclusions

1. The technology is based on the principles of responsible consumption and production, which corresponds to the concept of sustainable development of the agro-industrial sector of the economy. The sequence of technological stages has been justified, which include hydromechanical, hydrothermal processing of pea groats and vegetables, their grinding, as well as obtaining an emulsion based on pea aquafaba and its stabilization by introducing pregelatinized starch. The final product is obtained by combining all the above-mentioned semi-finished products, with subsequent storage of the product.

It was determined that when implementing justified technological parameters, the control points are as follows: the mass fraction of dry matter in aquafaba (4.6–4.8 %), the degree of grinding of pea groats and vegetables (the average particle diameter is $D_{4,3}$=127.1–138.0 μm and $D_{4,3}$=179.7–232.0 μm, respectively), the average diameter of the fat phase droplets in the product ($D_{4,3}$=13.7–16.8 μm), the viscosity of the freshly prepared product and after 30 days of storage (7.91–8.52 Pa·s and 8.01–8.43 Pa·s, at γ=40.0 1/s), and emulsion stability is (98–99%).

2. Sensory, physicochemical, and microbiological indicators of the vegetable appetizer, freshly prepared and after 30 days of storage, have been established. The product is characterized by a plastic, pasty consistency, a harmonious moderately pronounced carrot-pumpkin smell and taste. After 30 days of storage, the above-defined indicators are stable, which confirms the effectiveness of the selected technological solutions.

Vegetable appetizers contain 45.1 % of dry matter, which is represented by proteins (4.3 %), fats (25.9 %), carbohydrates (13.6 %), and minerals (1.3 %). The water activity in the studied samples, freshly prepared and after 30 days of storage, is 0.910 and 0.902, respectively. The main requirements regulating the quality and safety indicators of products are defined in the developed and approved technical conditions (TU 10.8-44234755-002:2024 "Appetizers based on legume raw materials") and technological instructions.

3. Evaluation of the rheological parameters of vegetable appetizers showed that they are food systems with high structural stability; they are characterized by the dominance of elastic properties over viscous ones with physical stability. Appetizers are characterized by thixotropic behavior, which is manifested in the ability to restore the original structure destroyed by mechanical action (restoration of the structure of the freshly prepared appetizer and after 30 days of storage is 86.78 % and 86.44 %, respectively). During storage, a slight compaction of the structure is observed, which is confirmed by an increase in the ultimate shear stress τ_0 from 45.2 to 49.9. At the same time, a decrease in the consistency coefficient from 96.7 Pa·s^n to 88.0 Pa·s^n and the flow behavior index from 0.301 to 0.235 indicates that the product becomes less viscous, fluid.

The study of the microstructure of the vegetable appetizer demonstrates a heterogeneous, complex, and multicomponent structure. All components of the appetizer are integrated into a single matrix, which ensures the physical stability of the product and sensory indicators. The presence of air inclusions in the form of pores, fat droplets evenly distributed in the product matrix, swollen starch grains and particles of crushed pea and vegetable grits create a holistic heterogeneous system. This forms an idea of the role of recipe components in the formation of the properties of the new product.

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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