Rheological structure assessment of the plant alternative to yoghurt

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Abstract. The growth in the number of people suffering from milk components intolerance implies the creation of their plant alternatives, corresponding in organoleptic characteristics, nutritional and biological values, but not having milk allergens. Therefore, development and study of the rheological properties of plant analogues of dairy products is relevant. The article discusses the structural and mechanical parameters of fermented plant products, from oatmeal powder, sunflower protein and with the use of starter cultures Streptococcus salivarius subsp. termophilus and Lactobacillus delbrueckii subsp. bulgaricus, depending on the mass fraction of pectin structurant and its shelf life. It is shown that, by the nature of the flow, the curves obtained refer to pseudoplastic liquids. It has been established that the destruction of the structure of the fermented plant product, and hence the decrease in effective viscosity, occurs in two stages: avalanche-like - at a shear rate of 5 to 24 s^{-1}; from 24 s^{-1} and further - with a damping speed relative to the beginning of destruction. The regression dependence of the effective viscosity change on the shear rate and pectin concentration has been calculated. It has been found that with an increase in the storage time of the samples, their hardness increases up to the seventh day. After that this indicator decreases, which characterizes gradual destruction of their structure. The hardness work, the adhesiveness, the adhesive force and the resilience of prototypes have been determined. The obtained research results correlate with the studies conducted in the field of rheological characteristics of fermented milk products.

1 Introduction

The strategy of scientific and technological development of the Russian Federation in the field of nutrition provides for the creation of safe and high-quality, including functional, food products until 2026-2031, as well as the efficient processing of agricultural products, due to the fact that developments and scientific and technical results in this area and others are the basis for the innovative development of the domestic market for products and services, as well as Russia's stable position in the foreign market [1]. This Strategy, as well as other

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regulatory documents, are aimed at improving life quality and preventing diseases among the population.

Currently, there is a rapid increase in the number of people suffering from food allergies [2]. In this regard, there is a need to develop alternative types of products that have the same qualities as the original products and comply with the biological value.

Dairy products, along with high nutritional value, also contain components such as albumins, caseins, lactose, which are included in the list of food allergens, which do not lose their properties even during heat treatment and fermentation and can have a negative effect on the human body. [2,3]. As a result of these facts, people suffering from milk protein intolerance cannot consume such an important food product as dairy and sour-milk products. The consequence of this aspect is a reduction in the intake of protein with high biological value and probiotics, which are important for maintaining the human microbiome.

Fermented plant products containing various lactic acid cultures, which are presented on the modern market in a limited assortment, can serve as equivalents of sour-milk drinks, including yogurts. However, these products are characterized by a low biological value of the protein, and their organoleptic and rheological characteristics differ significantly from traditional fermented milk drinks.

When developing new types of food products, metrological control of the consistency is important, which allows to purposefully influence the structural and rheological characteristics of the finished product. To predict newly developed fermented plant products with a given consistency, a database of rheological characteristics is needed, which can later be used in solving recipe problems and evaluating the rheological parameters of new types of food products.

The aim of the study was to evaluate the rheological structure of a plant product with lactic acid microorganisms.

To achieve this aim, the following tasks are solved:

1. Study of the influence of the mass fraction of pectin and the shelf life of the fermented plant product on changes in its structural and rheological properties;

2. Mathematical processing of the obtained results, obtaining regression dependencies that adequately describe rheological curves behaviour.

2 Materials and Methods

The following types of raw materials have been used for conducting the research: fermented oatmeal powder (manufactured by Green Lines LLC, TS 11.07.19-143-51070597-2020), sunflower protein (CS 41996709-001-2019), pectin (manufactured by Vita Pectin LLC), sourdough (BK-Uglich-STBv) that meet the requirements of TR TS 021/ 2011, TR TS 022/2011, TR TS 029/2012, TR TS 033/2013.

During the experiment, samples of mixtures for the production of fermented plant drinks have been compiled (Table 1).

Table 1. Formulations of samples of herbal product mixtures (excluding losses on operations), %

Components	Name of the samples		
	Sample 1	**Sample 2**	**Sample 3**
Oatmeal powder	12.0	12.0	12.0
Sunflower protein	3.2	3.2	3.2
Pectin	0.5	1.0	1.5
Water	84.3	83.8	83.3
Total	100	100	100

Source [Compiled by the authors]

The experimental samples have been prepared according to the technology of fermented milk drinks by the thermostatic method, shown in Figure 1 [4].

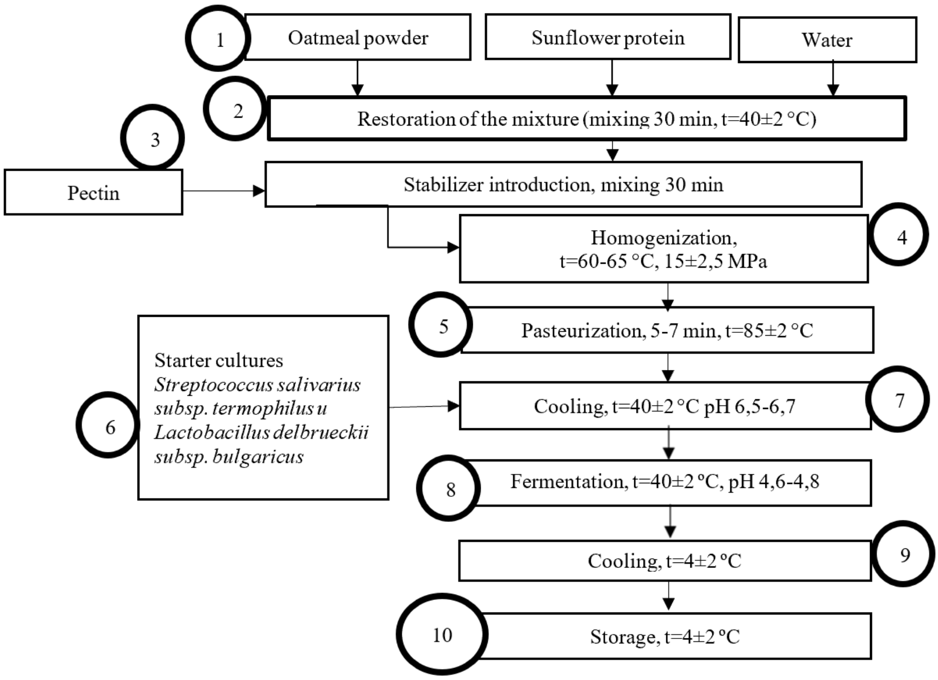

Fig. 1. Experimental samples production chart

In order to measure the structural and rheological properties of the samples of plant fermented products, the effective viscosity, rate and acceleration of structure destruction, hardness, hardness work, adhesiveness, adhesive force and resilience have been evaluated.

The viscosity of the samples was determined after fermentation and cooling of the samples (background) and on the 10th day of storage using a Brookfield DV-II + Pro rotational viscometer using an RV-3 spindle, the temperature of the test samples was 20±1ºC. The strength index in the samples was determined on days 1, 3, 7 and 10 of storage using a Brookfield CT3 texture meter using a cylindrical probe with a diameter of 20 mm, an immersion speed of 1 mm/s, an immersion depth of 15 mm, a load force of 10 g, a test temperature of 8±2ºC, ambient temperature 19±1ºC.

The rate and acceleration of the destruction of the product structure were calculated, respectively, as the first and second derivatives of the regression equation.

The hardness work (A1) and adhesiveness (A3) were calculated as positive and negative areas on the plot of load versus time (Fig. 2).

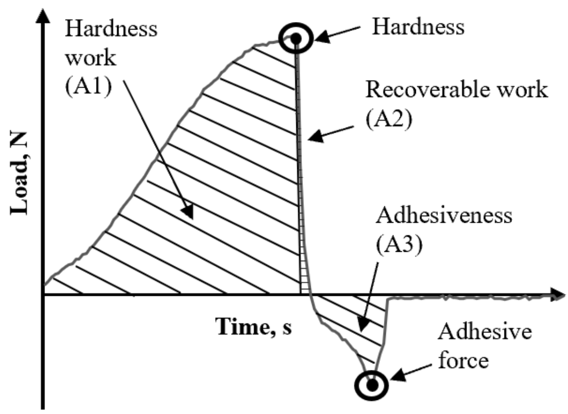

Fig. 2. Graph of load versus time

Resilience is calculated using formula 1:

$$Resilience = \frac{A_2}{A_1} \quad (1)$$

where A_2 – recoverable work, mJ; A_1 – hardness work, mJ.

All studies have been carried out in 3-5 replications. Mathematical processing of experimental data has been carried out using Microsoft Excel 2016.

3 Results

Among the large number of rheological parameters describing the consistency of food products, an important place is given to the viscosity and strength of their structure. Obtained objective physical values of these indicators can be used to control technological process and product quality. In addition, knowledge of physical and rheological characteristics (such as viscosity, hardness, adhesiveness of food products) depending on technological parameters is necessary when designing modern equipment and creating automated lines with a closed pipeline system [5].

Experimental data on the effective viscosity of the samples are presented in Table 2.

Table 2. Change in effective viscosity (mPa·s) of test samples depending on pectin concentration and shear rate

Shear rate, s^{-1}	Name of the samples					
	Sample 1		Sample 2		Sample 3	
	Background	10 days	Background	10 days	Background	10 days
5	640 ± 6	2750 ± 27	940 ± 9	7590 ± 76	1350 ± 13	10780 ± 108
24	327 ± 3	1054 ± 10	679 ± 7	2648 ± 26	985 ± 10	4350 ± 43
43	277 ± 3	757 ± 8	616 ± 6	1836 ± 18	872 ± 9	2558 ± 26
62	261 ± 3	609 ± 6	573 ± 6	1474 ± 15	797 ± 8	1774 ± 18
81	255 ± 3	522 ± 5	530 ± 5	1269 ± 13	738 ± 7	1358 ± 14
100	250 ± 2	481 ± 5	498 ± 5	1100 ± 11	687 ± 7	1100 ± 11

Source [Compiled by the authors]

The data presented in Table 2 show the nature of the flow curves of the samples of the plant product. Based on the obtained results, the equations of dependences of the effective viscosity on the shear rate have been derived, and it has been established that all of them are described by a power function and refer to pseudoplastic fluids [6].

The viscosity of the samples on the 10th day of storage increases on average 3-4 times (Table 2). Thus, in sample 1, the background values of viscosity at a shear rate of 5 s^{-1} were 640 mPa·s, and on the 10th day of storage, 2750 mPa·s; in sample 2, at the same shear rate, the viscosity was 940 mPa·s and 7590 mPa·s, respectively; in sample 3 – 135 mPa·s and 10780 mPa·s, respectively. This is probably due to an increase in the strength of the fermented clot of the plant product (Fig. 4) and strengthening of its colloidal physical structure during storage.

Based on the regression equations, the rate of destruction of the structure of plant products and the equation for accelerating the destruction of the structure have been calculated (Table 3), which are defined as the first and second derivatives of the regression equation, respectively [5,6].

Table 3. Equations for the destruction of the structure of test samples on the first day of research and during storage

Equations for the destruction of the test samples structure, characterizing	Name of the samples					
	Sample 1		Sample 2		Sample 3	
	Background	10 days	Background	10 days	Background	10 days
rate of destruction	$y = -278,84x^{-1,508}$	$y = -2313,50x^{-1,964}$	$y = -309,66x^{-1,341}$	$y = -6886,63x^{-2,054}$	$y = -483,78x^{-1,367}$	$y = -13590,65x^{-2,279}$
acceleration of destruction	$y = 420,49x^{-2,508}$	$y = 4543,72x^{-2,964}$	$y = 415,26x^{-2,341}$	$y = 14145,13x^{-3,054}$	$y = 661,33x^{-2,367}$	$y = 30973,10x^{-3,279}$

Source [Compiled by the authors]

Based on the equations for the rate and acceleration of the destruction of the structure of plant analogues of yoghurt presented in Table 3, we have obtained kinematic characteristics of the level of destruction of the structure on the background day of the study (Table 4) and on the 10th day of storage (Table 5).

Table 4. Background kinematic characteristics of structure destruction rate (mPa·s/s-1) and acceleration of structure destruction (mPa·s/s-2) of the test samples

Shear rate, s^{-1}	Name of the samples					
	Sample 1		Sample 2		Sample 3	
	Rate of the structure destruction, mPa·s/s^{-1}	Acceleration of the structure destruction, mPa·s/s^{-2}	Rate of the structure destruction, mPa·s/s^{-1}	Acceleration of the structure destruction, mPa·s/s^{-2}	Rate of the structure destruction, mPa·s/s^{-1}	Acceleration of the structure destruction, mPa·s/s^{-2}
5	24.62	7.43	35.77	9.59	53.60	14.65
24	2.31	0.15	4.37	0.24	6.28	0.36
43	0.96	0.03	2.00	0.06	2.83	0.09
62	0.55	0.01	1.22	0.03	1.72	0.04
81	0.37	0.01	0.85	0.01	1.19	0.02
100	0.27	0.00	0.64	0.01	0.89	0.01

Source [Compiled by the authors]

Table 5. Kinematic characteristics of change in the structure destruction rate (mPa·s/s^{-1}) and acceleration of the structure destruction (mPa·s/s^{-2}) of the test samples on day 10

Shear rate, s^{-1}	Name of the samples					
	Sample 1		Sample 2		Sample 3	
	Rate of the structure destruction, mPa·s/s^{-1}	Acceleration of the structure destruction, mPa·s/s^{-2}	Rate of the structure destruction, mPa·s/s^{-1}	Acceleration of the structure destruction, mPa·s/s^{-2}	Rate of the structure destruction, mPa·s/s^{-1}	Acceleration of the structure destruction, mPa·s/s^{-2}
5	98.06	38.52	252.54	103.74	346.97	158.15
24	4.50	0.37	10.07	0.86	9.72	0.92
43	1.43	0.07	3.04	0.15	2.57	0.14
62	0.70	0.02	1.43	0.05	1.12	0.04
81	0.41	0.01	0.83	0.02	0.61	0.02
100	0.27	0.01	0.54	0.01	0.38	0.01

Source [Compiled by the authors]

It can be seen from the presented data (Table 4) that the highest background destruction rate at a shear rate of 5 s^{-1} is observed in sample 3 (53.6 mPa·s/s^{-1}), and the lowest – in sample 1 (24.62 mPa·s/s^{-1}).

With an increase in the shear rate to 24 s^{-1} the rate of the structures destruction decreases by 8-10 times as compared to the beginning of the destruction. When the shear rate reaches 62 s^{-1} or more, the rate of the samples structure destruction is minimal and practically does not change.

On the 10th day of storage (Table 5) the highest rate of the samples structure destruction of the plant products is observed at the shear rate 5s^{-1} in sample 3 with the mass fraction of pectin 1,5% and equals to 346.97 mPa·s/s^{-1}, whereas the lowest-is in sample 1 with the mass fraction of pectin 0,5% (98.06 mPa·s/s^{-1}).

As the shear rate increases up to 24 s^{-1} , the rate of the structures destruction decreases 20-35 times as compared to the beginning of the destruction.

After summarizing the data, it is fair to say that the structure destruction of the fermented plant product, and hence the decrease in effective viscosity, occurs in two stages: avalanche-like – at a shear rate from 5 to 24 s^{-1}; from 24 s^{-1} and so on – with a decaying speed as compared to the beginning of destruction.

Mathematical processing of the obtained results made it possible to obtain regression equations that adequately describe the changes in effective viscosity depending on the concentration of pectin.

Figure 3 shows a graph of the change in the effective viscosity of the test samples from the shear rate and pectin concentration.

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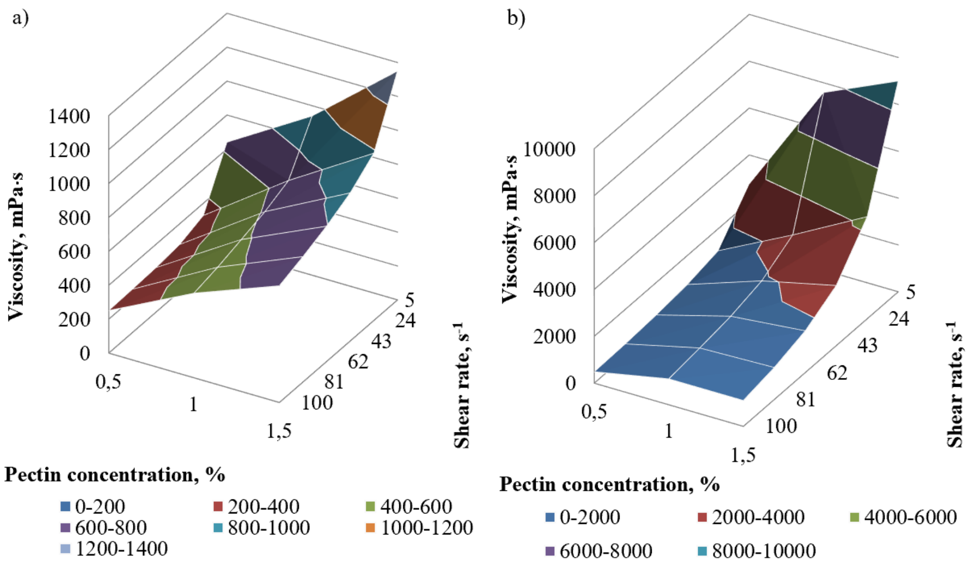

Fig. 3. Change in the effective viscosity of the test samples depending on the shear rate and pectin concentration: a – background, b – 10 days

The regression dependence of the change in effective viscosity on the studied two parameters is as follows:

Background:

$$y=293.7343+569.9167*x_1-4.51835*x_2, \quad (2)$$

where y-viscosity; x_1 – pectin concentration; x_2 – shear rate.

10 days:

$$y=2631.29+2327.79*x_1-49.772*x_2, \quad (3)$$

where y-viscosity, x1 – pectin concentration, x_2 – shear rate.

Important rheological parameters that characterize the structural and mechanical properties of the experimental samples are: hardness, hardness work, adhesiveness, adhesive force, resilience etc.

Data on the structural and mechanical properties of the test samples depending on their shelf life are presented in Figure 4. The hardness of the samples is presented on the graphs as positive peak values, the adhesive force - as negative peak values, the hardness work - the positive area (A1), adhesiveness - the total negative area (A3) (Fig.2).

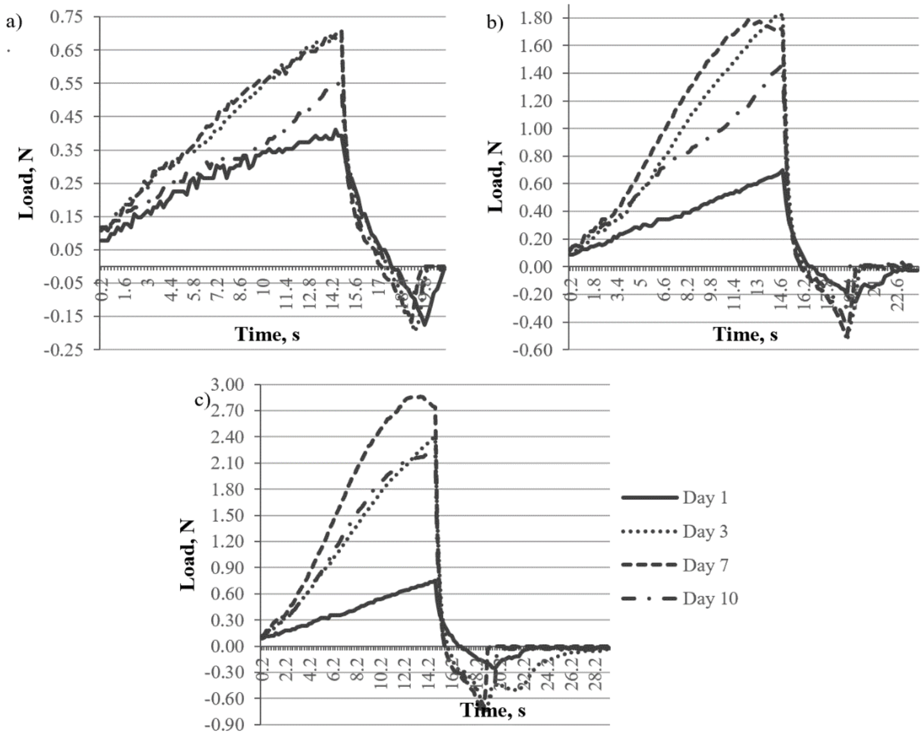

Fig. 4. Determination of the test samples hardness in terms of load depending on the time of measurement of the indicator and pectin concentration: a – Sample 1, b – Sample 2, c – Sample 3

Based on the data obtained, the numerical values of the structural and rheological characteristics of the samples have been calculated and presented in Table 7 – 9.

Table 6. Change of the rheological parameters of sample 1 depending on the shelf life

Parameters	Sample 1			
	Day 1	**Day 3**	**Day 7**	**Day 10**
Hardness (N)	0.41	0.69	0.71	0.55
Hardness work (mJ)	3.95	6.30	6.44	4.69
Adhesiveness (mJ)	1.15	1.05	0.87	0.52
Adhesive force (N)	0.18	0.20	0.17	0.10
Resilience	0.50	0.32	0.23	0.32

Source [Compiled by the authors]

Table 7. Change of the rheological parameters of sample 2 depending on the shelf life

Parameters	Sample 2			
	Day 1	**Day 3**	**Day 7**	**Day 10**
Hardness (N)	0.70	1.83	1.78	1.46
Hardness work (mJ)	5.58	13.77	15.67	11.17
Adhesiveness (mJ)	3.24	4.11	3.91	2.44
Adhesive force (N)	0.25	0.53	0.50	0.39
Resilience	0.28	0.16	0.12	0.14

Source [Compiled by the authors]

Table 8. Change of the rheological parameters of sample 3 depending on the shelf life

Parameters	Sample 3			
	Day 1	**Day 3**	**Day 7**	**Day 10**
Hardness (N)	0.76	2.39	2.86	2.23
Hardness work (mJ)	6.06	18.30	24.77	18.84
Adhesiveness (mJ)	3.42	6.61	6.63	8.16
Adhesive force (N)	0.25	0.74	0.77	0.74
Resilience	0.31	0.15	0.10	0.10

Source [Compiled by the authors]

From the presented data, it can be seen that the adhesiveness of sample 1 over the entire study period is the smallest and amounts to 1.15 mJ on the first day of storage. For samples 2 and 3 the values of this indicator are almost the same and amount to 3.24 and 3.42 mJ, respectively. The data obtained show that an increase in the mass fraction of pectin above 1.0% does not significantly affect this indicator at the initial stage of production. During storage, the strength of all samples of fermented plant products increases and reaches its maximum values on the 7th day of storage. The higher the mass fraction of pectin in the samples is, the more their consistency is strengthened during storage (for samples with a mass fraction of pectin of 0.5%; 1.0% and 1.5%, the indicator increased by 1.7; 2.6 and 3.8 times, respectively). Further, the strength index begins to decrease, and there occurs a gradual destruction of the structure of the samples, which correlates with the effective viscosity data obtained during their storage (Table 2).

If we analyze the strength of the samples structure depending on the mass fraction of the pectin structurant, then over the entire storage period, sample 1 (with a lower pectin content) shows a softer consistency (positive area, Fig. 4a), with significantly less hardening during storage.

The data obtained, characterizing the structural and rheological properties of the experimental samples of fermented plant products, correlate with the data published in the scientific literature in the study of functional yoghurts containing various plant fillers. Researchers have noted their influence on the viscosity and strength of the structure of the product under study [7-13]. The resulting enriched products had a viscosity in the range of 0.59–18.4 Pa·s depending on the type of the filler, its mass fraction, samples temperature, and also had hardness in the range of 0.37-2.48 N [7-13]. The obtained values of the adhesive force in comparison with the literature data on the adhesive force of fermented milk products are also in the same numerical range [6].

4 Conclusions

Structural and rheological characteristics of a plant alternative to a fermented milk product have been studied using starter cultures of Streptococcus salivarius subsp. termophilus and Lactobacillus delbrueckii subsp. bulgaricus depending on the mass fraction of pectin structurant and the terms of its refrigerated storage.

It has been found that the viscosity of the experimental samples increases by an average of 3-4 times on the 10^{th} day of storage. It has been shown that the destruction of the structure of the fermented plant product and the effective viscosity decrease occurs in two stages: avalanche-like - at a shear rate of 5 to 24 s^{-1}; from 24 s^{-1} and further - at a decaying speed relative to the beginning of destruction.

Regression equations for changes in effective viscosity depending on pectin concentrations (x_1) and shear rate (x_2) have been obtained, which adequately describe the changes in the effective viscosity depending on the pectin concentration:

$y=293.7343+569,9167*x_1-4.51835*x_2$ (background); $y=2631.29+2327.79*x_1-49.772*x_2$ (10^{th} day of storage).

It is shown that during storage, the hardness of samples of fermented plant products increases and reaches its maximum values on the 7th day of storage, then the hardness begins to decrease and gradual destruction of the samples structure is observed. It has been found that the higher the mass fraction of pectin in the samples is, the more their consistency is strengthened during storage (for samples with a pectin mass fraction of 0.5%; 1.0% and 1.5%, the indicator increased by 1.7; 2.6 and 3.8 times respectively).

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