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Modeling the process of enzymatic extraction of pectin substances from red beet (*Beta vulgaris L. var. conditiva*) using an extractor equipped with an ultrasonic emitter and a high-speed mixer

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Abstract

Deep processing of fruit and vegetable products is one of the most important tasks for providing the population with functional food products. This article presents an analytical review and research on the extraction of pectin from plant raw materials in order to obtain a pectin-containing extract. The aim of the study is to increase the yield of pectin during enzymatic extraction of red beet pomace. The effect of ultrasonic processing of raw materials on the yield of pectin during enzymatic extraction from red beet was studied - the optimal intensity of ultrasound processing was 50 kW/m^2 at a frequency of 25 kHz. The effect of the extragent mixing rate on the pectin yield during enzymatic extraction from red beet was studied - the optimal speed of the mixer was 1000 rpm. The results of experiments showed that the use of an ultrasonic emitter in the extractor design, as well as a high-speed mixer, will significantly increase its efficiency by 19-21%. The main functional properties of the obtained samples of red beet pectin extract were also studied. Mathematical modeling of the process of extracting pectin on the proposed equipment is carried out and a criterion equation is proposed that characterizes the intensity of extraction (the intensity of mass transfer in the solid - liquid system). The main functional properties of red beet pectin extract samples were also studied. In vitro, low-esterified pectin from red beet has more pronounced reducing properties than the antioxidant drug Emoxipine, which confirmed the possibility of using the resulting pectin extract as a dietary supplement.

Keywords: extractor, ultrasonic extraction, beet processing, pectin, functional nutrition

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INTRODUCTION

One of the most important directions to improve the efficiency of modern production is to involve secondary raw materials in processing (Kusainova, 2008). The use of secondary raw materials for processing red beet during its processing (production of juices and purees) to obtain pectin-containing extract is considered profitable, since its content in such raw materials is from 0.6 to 1.2%. (Mazz Marry et al., 2000).

Pectin is an important carbohydrate polymer that can protect the body from exposure to radioactive and heavy metals (lead, strontium, and others), delay the development of harmful microorganisms in the intestine, and remove cholesterol (Thakur et al., 1997; Levchenko, 2003).

In addition to using pectin as a drug, pectin powder and pectin concentrate are added to the diet to enrich special-purpose dishes. Pectin diets are recommended for preventive nutrition for workers who are in contact with heavy metal dust. Adding pectin to the diet improves the body's metabolic reactions, regulates the digestive process, and normalizes the functioning of organs and systems in general (Golubev, 2005; Aimukhamedova and Shelukhin, 2007). In addition, its presence is necessary for the stable preservation of the complex of vital vitamins and microelements, as well as for their full assimilation by the body (Ivanova and Ershova, 2012; Degtyarev, 2007). Based on the above, the development of effective technology and equipment for extracting pectin and enriching food products with it is an urgent task.

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In cells, pectin molecules are associated with cellulose, hemicellulose and lignin, which prevents its complete hydrolysis, so the methods used to isolate pectin are long and time-consuming. therefore, improving the equipment and methods of its extraction is a priority (Kolesnikov, 2006). The recommended daily dose of pectin for adults is 3-4 g, and for children - 1-2 g (Robert, 1997).

The most common raw material for the production of pectin is apple and citrus fruit pomace. Hydrolysis-extraction is carried out in a batch extractor with an aqueous solution of nitric (hydrochloric) acid. The average dry matter content in the extract is 1.0-1.2 %, including 0.3-0.4 % of pectin substances. The extract is separated and filtered (Colin, 1990).

In this research, red beet pomace was used as a vegetable raw material for obtaining pectin-containing extract, since this secondary raw material is not expensive, and the percentage of pectin in it is not inferior to citrus and apple pomace. Beet pulp contains 15-30% pectin from the total dry matter mass and is increasingly considered the best alternative raw material for the production of pectin and pectin-containing extract (Velyamov et al., 2019, 2019; Yapo et al., 2007). It should also be noted that in addition to pectin, red beet contains two main water-soluble pigments - betalaines, including red-purple betacyanins and orange betaxanthins (Velyamov et al., 2019, Jackman and Smith, 1996; Gasztonyi et al., 2001; Stintzing and Carle, 2004; Gengatharan et al., 2015; Mereddy et al., 2017). Betalain foods (such as red beets) and their products have great potential for use as a natural food coloring agent (Velyamov et al., 2019, Jackman and Smith, 1996; Gasztonyi et al., 2001; Celli and Brooks, 2017) and as a functional food (Gengatharan et al., 2015).

The traditional technology for producing pectin, used by most foreign companies, is based on acid-thermal hydrolysis and subsequent alcohol deposition from the hydrolysate, using mixtures of alcohol with acid of different concentrations, strong acids (HCl, HNO_3, H_3PO_4, H_2SO_4), aluminum chloride and ammonium hydroxide, creating an aggressive working environment and harmful working conditions. The production process takes place at elevated temperature conditions (45... 120°C) in an acidic environment at pH = 0.5-2.0 with fluctuations in the extraction and hydrolysis time from 3 to 6 hours and a total process cycle of up to 12 or more hours. However, the complexity of the acid-alcohol method for producing pectin causes the high price of the target product, making this unique natural product inaccessible to the majority of the population (Garna et al., 2007; Lv et al., 2013).

The most modern, environmentally friendly method for producing pectin is a biotechnological method based on the action of microbial enzymes used as hydrolyzing agents. Enzymatic hydrolysis has a number of undeniable technological advantages, the main of which is to increase the yield of pectin while maintaining its gelatinous properties (Velyamov et al., 2019, Franchi et al., 2014).

In this research, a biotechnological method for obtaining pectin-containing extract from red beet pomace patented in the Republic of Kazakhstan (patent #29264) is used. Today, there is a question of mechanization of the enzymatic technology for obtaining pectin-containing extract, in particular, it is necessary to develop the design and hardware of the plant raw material extractor, which allows the most efficient production of the pectin extraction process.

One of the most modern methods of intensifying the yield of target components from a plant cell is the use of ultrasound. Ultrasonic waves generate a cavitation effect in the solvent, which leads to faster movement of molecules and deeper penetration of the solvent into plant cells (Toma et al., 2001; Corbin et al., 2015).

In addition to ultrasound, active mixing of the extragent during extraction of soluble substances will have a positive effect on the rate of pectin yield due to acceleration of mass transfer processes and leaching of soluble substances from plant raw materials. In this research, a high-speed propeller-type blade mixer was used to mix the low-viscosity extragent.

Today, propeller mixers are supplied with speed-change boxes that allow to change the number of revolutions, which further facilitates their use in semi-production conditions (Saraswathi, 2016).

Propeller mixers are mainly used for the following purposes:

- intensive mixing of low-viscosity liquids;
- preparation of suspensions and emulsions;
- agitation of precipitation containing up to 10% of the solid phase consisting of particles up to 0.15 mm in size.

Thus, the main advantages of the propeller mixer are: high mixing intensity and moderate power consumption, even with a significant number of revolutions (Saraswathi, 2016).

Based on the above, the creation of an extractor equipped with an ultrasonic emitter and a high-speed mixer will significantly reduce the time of pectin extraction, which will increase the yield of the final product.

METHODS OF RESEARCH

Vegetable raw materials. As a plant raw material for obtaining pectin-containing extract, a red beet variety zoned in the Republic of Kazakhstan - “Bordo” - was selected at the stage of technical ripeness. Previously, the root vegetables were processed into juice, and a pectin-containing extract was obtained from the pomace. The particle size of vegetable raw materials is 1.5-2 mm (Velyamov et al., 2019).

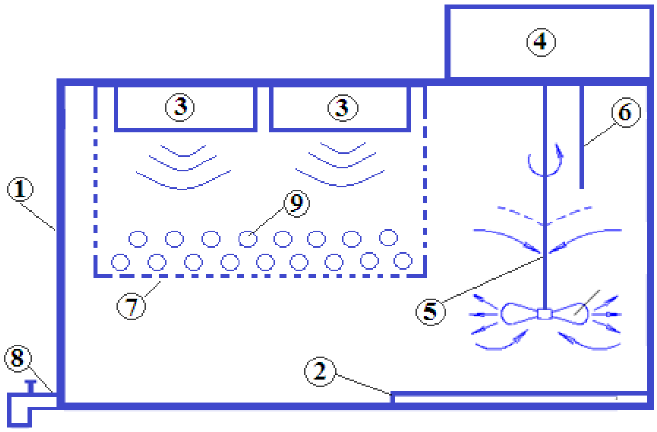

Fig. 1. Diagram of the proposed design of the plant raw material extractor

Experimental model. To conduct research, we created an experimental model of an open-type extractor equipped with an ultrasonic emitter, a heating element, and a high-speed mixer (**Fig. 1**). During the operation of the extractor, the plant raw materials are placed in a grid completely immersed in the liquid phase under the influence of ultrasound to destroy plant cells, while the liquid phase is actively mixed and heated to the desired temperature, which ensures the leaching of the extracted substance. At the end of extraction, the liquid and solid phases are easily separated (Velyamov et al., 2019).

The extractor for plant raw materials contains a heat-resistant body 1, a heating element 2, an ultrasonic emitter 3, a control computer 4, a high-speed mixer 5, a temperature sensor 6, a metal sieve for loading and unloading plant raw materials 7, a tap for draining the extract 8.

When calculating the geometric characteristics of the extractor, it is based on the location of plant raw materials in the near zone of ultrasonic waves relative to ultrasonic emitters, since the sound pressure decreases in the far zone of the sound field, which reduces the effectiveness of the impact. Calculation of the required volume of the extractor is calculated depending on the weight of the loaded raw materials, for 1 kg of raw materials, taking into account the technological reserve - 15 liters of water.

According to the standards and rules for the design of food and chemical equipment, depending on the technological conditions of the process, an average ratio is used to calculate the diameter of the mixer blades:

$$D/d = (1.5, \ldots, 2, \ldots, 3), (1) \quad (1)$$

where:

D - internal diameter of the device body, m.

d - diameter of the mixer blades, m.

To calculate the operating power of mixing, use the Euler criterion equation.

In this research, for an extractor designed to load 1 kg of plant raw materials (red beet pomace), selected:

- type II electric drive with one intermediate support, MP02 type gear motor and A02 series electric motor with a power of 75 W with an adjustable shaft speed up to n = 1000 rpm. The drive consists of a gear motor, two couplings, an intermediate shaft, racks, shaft seal and a mixing device;

- EHTs (electric heater tube) with power P = 6 kW. Material - stainless steel. EHT in the block - 3 pcs. Full length 450 mm. Laying EHTs produced in the sole size a = 200 mm, b = 250 mm;

- ultrasonic emitter of electroacoustic type (piezoelectric converter) of the company “RELTECH” - PMS-6-18. Electric power $R_{el.}$ = 6 kW. Acoustic power 1.8-5 kW.

In accordance with the standards of food and chemical equipment, the sieve device is made of thin-sheet steel of food grades (X18N10T) with holes with a diameter of 1.5 mm.

Conducting enzymatic extraction and quantitative determination of pectin. Pectin extraction was performed according to a method patented in the Republic of Kazakhstan (patent #29264). According to this method, pectin extraction is carried out in an aqueous medium at the rate of 1:13 - per 100 grams of dried red beet pomace 1300 ml of water. The medium temperature during swelling of plant raw materials is 56°C (for 15-18 hours), the medium temperature during enzymatic extraction is 37°C (for 4 hours) at pH = 7.2±0.1, the amount of the introduced multienzyme complex in the reference point for the pectinolytic enzyme pectinase is 20000 activity units, in this case, a multienzyme complex of the company “Bio JSC”, Belgium - with the activity of component enzymes (units/g): pectinase - 2000, cellulose - 350, i.e. 10% of the mass of the taken dry plant raw materials (Velyamov et al., 2014) is used.

The pectin content was determined by titrimetric method in accordance with GOST 29059-91 - Products of fruit and vegetable processing titrimetric method for determining pectin substances:

Table 1. Change range of the input factors

Planning conditions	Change range of the factors		
	X_1, rpm	X_2, kW/m ^{2}	X_3, h
High level Levels of factor variation	1000	150	5
Low level	600	50	1
Variability interval	200	50	1
The main levels of the factors	800	100	3
Levels of factor variation	200	50	2
Relations	4	2	1.5

Table 2. Matrix of planning conditions for conducting experiments

# of experiment	X_1		X_2		X_3	
	Code	rpm	Code	kW/m^2	Code	h
0	-	0	-	0	+	5
1	-	600	+	150	+	1
2	+	600	+	150	+	3
3	+	600	+	150	+	5
4	+	600	-	150	+	3
5	+	600	-	150	+	5
6	-	1000	+	50	+	1
7	+	1000	+	50	+	3
8	+	1000	+	50	+	5
9	+	1000	-	50	+	3
10	-	1000	+	50	+	5
11	-	800	+	100	+	1
12	+	800	+	100	+	3
13	+	800	+	100	+	5
14	+	800	-	100	+	3
15	+	800	-	100	+	5

1. 50 ml of 0.4% caustic sodium solution (for saponification) is added to 30-50 ml of the sample (settling for 12 hours).
2. Add 50 ml of 1 normal acetic acid and 50 ml of 11.1 percent calcium chloride solution to precipitate pectin.
3. Filtration of sediment through a filter that has been pre-dried to a constant weight.
4. Precipitate is washed with a 0.5% solution of calcium chloride, then abundantly washed with cold distilled water to get rid of calcium chloride (check for reaction to chlorine with silver nitrate).
5. Rinsing with hot water to remove salts.
6. Filters with precipitation of calcium pectate are dried to a constant weight at 105°C.
7. Recalculation is performed using the following formula:

$$P = (a-b) \cdot 0.9235 \cdot 100\% / n, \quad (2)$$

where:

P - pectin substances, %;

a - weight of the filter with sediment, g;

b - weight of the filter dried to a constant weight, g;

0.9235 - coefficient of conversion of calcium pectate to pectin acid;

n – batch weight, g.

2.4 Investigation of optimal parameters of pectin extraction. The main factors influencing the process of pectin extraction from plant cells were selected:

X_1 - the rotation frequency of the mixing device, rpm;

X_2 - intensity of ultrasound exposure, kW/m^2

X_3 - exposure (duration of the process), h

The following indicator was used as the yield parameters of the experiment:

Y - the yield of pectin relative to the mass of its content in 100 g of raw material.

To determine the optimal duration of extraction, samples were taken every hour - for 5 hours, since the previously worked method (patent #29264) had a maximum extraction time of 5 hours and the main purpose was to reduce the extraction time and increase the yield of pectin from plant raw materials.

All these factors are compatible and non-correlated limits of changes in the studied factors are shown in **Table 1**.

Under the influence of ultrasonic waves with a frequency of 18-30 kHz and an intensity of 50-150 kW/m^2 passing through the chamber with the processed raw material, cavitation breaks the cell shell, partially depolymerizes protopectin, and intensifies the penetration of the extragent into the raw material and the diffusion of soluble pectin into the solution (Agopyan and Ershov, 2005).

The maximum speed of the blade mixer was 1000 rpm, further increase in speed formed excessive foaming when extracting pectin from red beet pomace with water.

A first-order planning matrix was used to conduct a multi-factor experiment. In total, 15 experiments were carried out during the implementation of the experiment, three of them are in the center of the plan. The control experiment was carried out without the use of ultrasound and active mixing (**Table 2**).

The result of multiple statistical analysis of extraction process of pectin from plant raw material can obtain the regression equation and graph the response surface, the analysis of which will identify the factors most

Table 3. Results of a multi-factor experiment

# of experiment	Rotation frequency of the mixing device, X_1		Intensity of US, X_2		Duration of the extraction, X_3		Yield of pectin, % , of the total mass in the feedstock				S^2_n
	Code.	rpm	Code.	kW/m^2	Code.	ч	y_1	y_2	y_3	$\bar{y}$	
0	-	0	-	0	+	5	65.0	65.1	64.9	65.0	0.01
1	-	600	+	150	+	1	49.4	49.5	49.1	49.3	0.11
2	+	600	+	150	+	3	74.1	74.8	74.5	74.5	0.25
3	+	600	+	150	+	5	72.5	72.3	72.2	72.3	0.21
4	+	600	-	150	+	3	54.3	54.7	54.4	54.5	0.27
5	+	600	-	150	+	5	64.3	64.7	64.8	64.6	0.28
6	-	1000	+	50	+	1	45	44.9	45.2	45.0	0.13
7	+	1000	+	50	+	3	78.7	78.5	78.8	78.7	0.11
8	+	1000	+	50	+	5	76.4	76.3	76.2	76.3	0.28
9	+	1000	-	50	+	3	64.6	65.2	65.3	65.0	0.11
10	-	1000	+	50	+	5	62.5	62.9	62.9	62.8	0.02
11	-	800	+	100	+	1	45.6	45.3	45.8	45.6	0.43
12	+	800	+	100	+	3	75.8	75.4	75.5	75.6	0.45
13	+	800	+	100	+	5	73.2	73.5	73.3	73.3	0.21
14	+	800	-	100	+	3	61.2	61.8	61.5	61.5	0.01
15	+	800	-	100	+	5	63.7	64.1	63.9	63.9	0.01
	S_E = 2.88										

influencing the process of extraction of pectin from plant raw materials by the example of red beets, and also solve the optimization problem of finding the change range of input parameters.

Mathematical model of the process of enzymatic extraction of pectin substances from red beet (Beta vulgaris L. var. conditiva) using an extractor equipped with an ultrasonic emitter and a high-speed mixer. The mathematical model of the periodic extraction process was based on the generally accepted theory and laws of processes and devices of food production and chemical technologies.

Study of the main functional parameters of the obtained pectin extract from red beet. The resulting 1% pectin solution was studied for antioxidant activity and compared with the antioxidant activity of the antioxidant drug: Emoxipin - 1% solution (FSUE “Moscow endocrine plant”, Moscow).

The antioxidant activity of the tested substances was studied based on the evaluation of the reducing activity of the studied substances (the FRAP method). 0.04 ml of 0.1, 0.5, or 1% drug solution was added to 0.3 ml of the incubation mixture containing 0.5 μm $FeCl_3$ solution, 0.25 μm 2,4,6-tripyridyl-S-triazine solution in 1 μm HCl and 75 μm acetate buffer (pH 3.6). The reducing activity was determined using a spectrophotometric method by the amount of a colored Fe^{2+} complex formed within 60 minutes with 2,4,6-tripyridyl-S-triazine at a wavelength of 593 nm and expressed in μm of Fe^{2+} (Kolenchenko et al., 2005).

RESULTS AND DISCUSSION

Results of the research of optimal parameters of pectin extraction

To optimize the parameters of pectin extraction from plant raw materials, a multi-factor experiment was performed on the example of red beet pomace (**Table 3**) according to the experiment planning given in section 2.4.

Based on the obtained experimental data, make the regression equation (3). The main factor indicators are: X_1 - mixing intensity, X_2 - intensity of ultrasound exposure, X_3 - exposure (duration of the process).

$$У=64.193+50.68\cdot X_1+43.567\cdot X_2+64.193\cdot X_3 - 50.68\cdot X_1^2 + 47.123\cdot X_1\cdot X_2 -57.436X_1\cdot X_3 - 43.567\cdot X_2^2 +53.88\cdot X_2\cdot X_3 - 64.193\cdot X_3^2 \quad (3)$$

The interpretation of the resulting model is presented in the form of graphs of response surfaces in **Fig. 2**.

Thus, three parameters have a positive effect on the yield of pectin (extraction time, active mixing, and intensity of ultrasonic processing), especially ultrasonic processing and mixing. However, an excessive increase in the intensity of ultrasonic processing and its duration leads to the destruction of pectin, so it is necessary to observe the technological regime without exceeding the norm.

Mixing affects the yield of pectin due to its leaching from the plant raw material located in the grid. With increasing mixing activity, external diffusion (mass transfer from the surface of the plant raw material particle to the surrounding extragent) increases sharply.

The optimal intensity of ultrasound processing was 50 kW/m^2 at a frequency of 25 kHz. The optimal speed of the mixer was 1000 rpm.

The maximum yield of pectin under the combined effect of all three parameters was 78.7 % and 2 hours faster. Thus, it can be concluded that the use of this equipment is 19-21% more efficient than standard fermenters and 2 hours faster.

Mathematical model of the process of enzymatic extraction of pectin substances from red beet (Beta vulgaris L. var. conditiva) using an extractor equipped with an ultrasonic emitter and a high-speed mixer. The material balance for any section of the periodic process

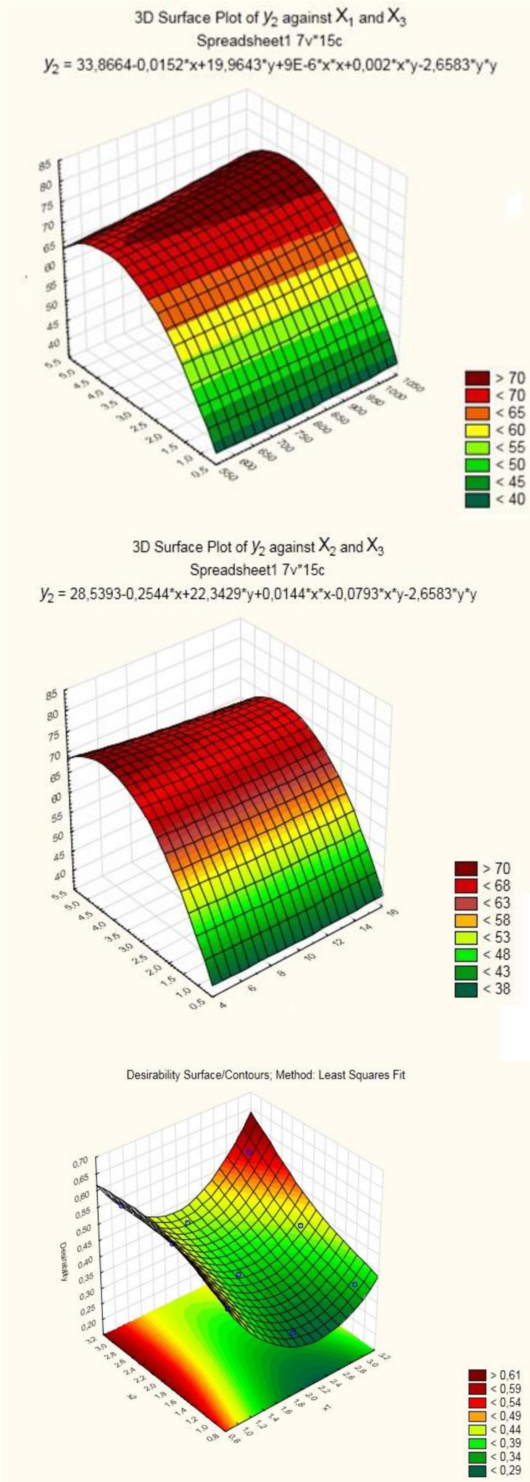

Fig. 2. Response surfaces of pectin yield depending on the natural values of the factors

device (in our case, the first case occurs) will take the form:

$$G \cdot dC = L \cdot dc, \quad (4)$$

where:

G - mass of the solvent in the solid, kg;

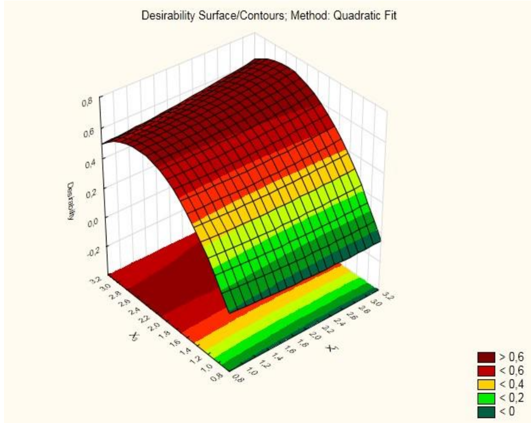

Fig. 2 (continued). Response surfaces of pectin yield depending on the natural values of the factors

L - mass of the solvent (extragent) received in the device, kg;

dC - infinitely small change in the concentration of the extracted substance in a solid, kg/kg;

dc - infinitely small change in the concentration of the extracted substance in solution, kg/kg.

From formula 5 we get:

$$G \cdot (C_i - C_f) = L \cdot (c_i - c_f), \quad (5)$$

where:

C_i and C_f - respectively, the initial and final mass concentrations of the extracted substance in the solid, kg/kg;

c_i and c_f - respectively, the initial and final mass concentrations of the extracted substance in solution, kg/kg;

For any arbitrarily accepted section of the device with a concentration of phases (***c*** and ***C***), the material balance equation will take the form:

$$\int_{C}^{C_i} G dC = \int_{c}^{c_f} L dc$$

we get:

$$G \cdot (C_i - C) = L \cdot (c_f - c), \quad (6)$$

where:

c; C - current concentration variables at any given time.

Expression (6) is an equation of the working line of the process.

In the actual extraction process, the physical conditions along the length of the device change for the following reasons:

1) changes in temperature, concentration, and structure of solid particles lead to changes in the diffusion coefficient (D);
2) the ratio of mass flows of interacting media changes significantly;
3) change the size and elasticity of the extracted particles;

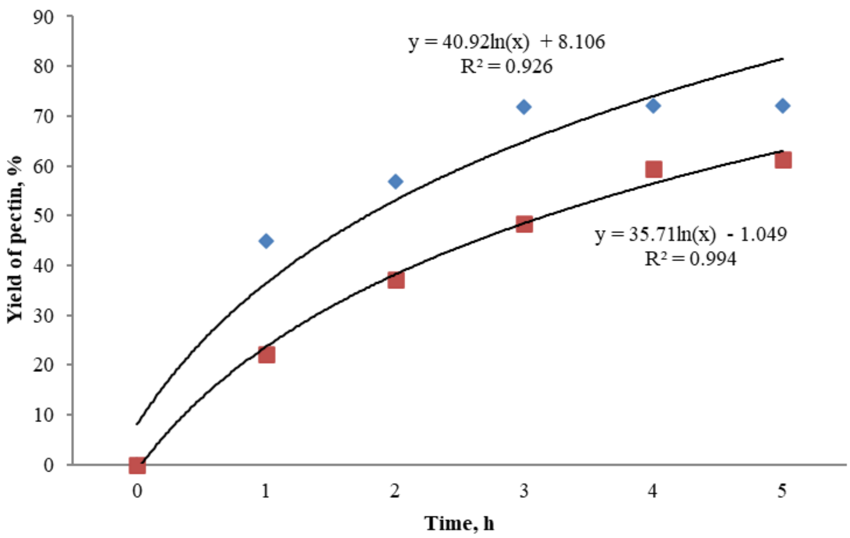

Fig. 3. Yield of pectin from beetroot pomace with active mixing of the extragent (experimental data)

4) for these reasons, the mass transfer coefficient changes along the length of the device.

All these factors (1-3) can significantly change the nature of extraction. In some parts of the device, the process may be characterized not by counter-flow, but by complete mixing.

A fairly accurate mathematical description of the extraction process is obtained on the basis of the equation that characterizes the Fourier diffusion criterion, considering the process not as a whole, but by individual intervals.

The intervals along the device length (in time) should be sufficiently large compared to the size of the extracted particles, but at the same time so small that it would be possible to assume the physical conditions of the process constant within the interval, and the extraction line on the interval - straight.

Thus, the problem is reduced to finding the concentration field at the end of the interval in a uniformly moving solid of a certain shape and size under constant physical conditions, the linear nature of the concentration change in the liquid surrounding this body, and the distribution of the concentration in the solid known at the beginning of the interval.

In practice, in the process of extraction from a solid by various solvents, two cases are observed that are taken into account in the material balance:

1) a number of components are in a solid in a dissolved state, and during the extraction process, the same substances are used as a solvent in which the extracted components are dissolved. In this case it is water;

2) some components are found in the solid as complexes of molecules that are sorbed on the inner and outer walls of cells. For their dissolution with the purpose of subsequent diffusion from the solid to the solution, a certain amount of a special organic solvent is necessary.

The calculation of the mass transfer coefficient (*β*) from the particles of plant raw materials to the liquid in the layer is recommended by V.N. Stabnikov according to the criteria equation of the form:

$$Nu_D = 3.8 \cdot 10^{-4} \cdot \mathrm{Re}^{1.38} \cdot \mathrm{Pr}_D{}^{0.23}, \quad (7)$$

For plant raw materials it is more preferable to use the equation:

$$Nu_D = 0.08 \cdot \mathrm{Re}^{0.5} \cdot \mathrm{Pr}_D{}^{0.33}, \quad (8)$$

According to the experimental data, it is shown that mixing and ultrasonic influence on the medium increases the mass yield of pectin. The intensity of the process due to mixing is taken into account by the value of Re. It is necessary to take into account in equation (6) the factors (criteria) for the action of heating and ultrasound.

In this research, a factor (criterion) of the thermal effect ***Te*** is proposed.

$$Te = \frac{t_n}{t_0}, \quad (9)$$

The criterion of ultrasonic impact ***Us*** is also proposed.

$$Us = \frac{J}{Z}, \quad (10)$$

where:

J - ultrasound intensity, kg/m^2·s

Z - wave resistance, kg/m^2·s

As a result, according to the similarity theory, we get a criterion equation of the form (taking into account all the intensification factors specified in section 2.3):

$$Nu_D = 0.08 \cdot \mathrm{Re}^{0.5} \cdot \mathrm{Pr}_D{}^{0.33} \cdot Te^m \cdot Us^n \quad (11)$$

Based on the results of processing curves in graphs (**Figs. 3-4**) we get the values of power indicators *m* =0.21; *n* =0.01.

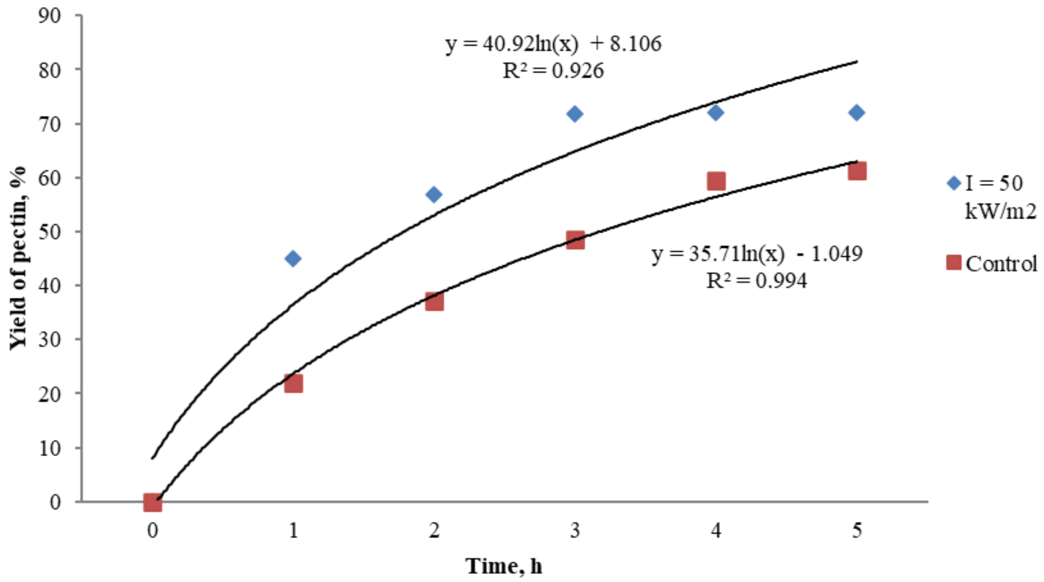

Fig. 4. Yield of pectin from beetroot pomace using an ultrasonic emitter (experimental data)

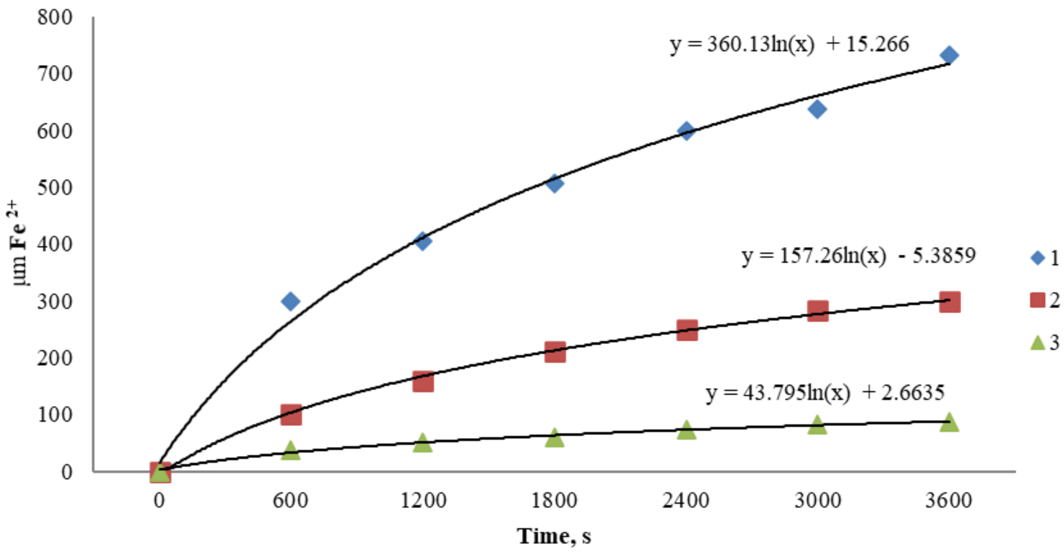

Fig. 5. Dynamics of reduction of trivalent iron with low-esterified pectin from red beet (in vitro)

Thus, in this research, a criterion equation of the form is proposed:

$$Nu_D = 0,08 \cdot \mathrm{Re}^{0,5} \cdot \mathrm{Pr}_D{}^{0,33} \cdot Te^{0,21} \cdot Us^{0,01} \qquad (12)$$

Equation (12) characterizes the intensity of extraction (the intensity of mass transfer in a solid - liquid system). After calculating the right part, determine the value of the Nusselt criterion (Nu_D). Knowing the Nu_D, determine the mass transfer coefficient *β*. Then calculate the transferred amount of substance (pectin) to the extragent using the mass transfer equation.

Results of studies of the main functional parameters of the obtained pectin extract from red beet. In a series of experiments, the regenerative activity of low-esterified pectin from red beet was compared with the reduction of trivalent iron under in vitro conditions, with an antioxidant agent, a drug called Emoxipine (**Figs. 5**-**6**).

The amount of reduced iron formed in the reaction with 1% pectin solution after 60 minutes of incubation was 740.5 ± 18.8 μm Fe^{2+}, with 0.5% solution - 415.3 ± 10.1 μm Fe^{2+} and with 0.1% solution - 101.2 ± 3.7 μm Fe^{2+} (**Fig. 5**).

The amount of reduced iron formed in the reaction with 1% Emoxipine solution after 60 minutes of incubation was 49.1 ± 1.0 μm Fe^{2+}, with 0.5% solution - 38.1 ± 0.9 μm Fe^{2+}, with 0.1% solution - 25.8 ± 0.6 μm Fe^{2+} (**Fig. 6**).

As can be seen from the results, Emoxipine had a lower reduction capacity compared to pectin. An

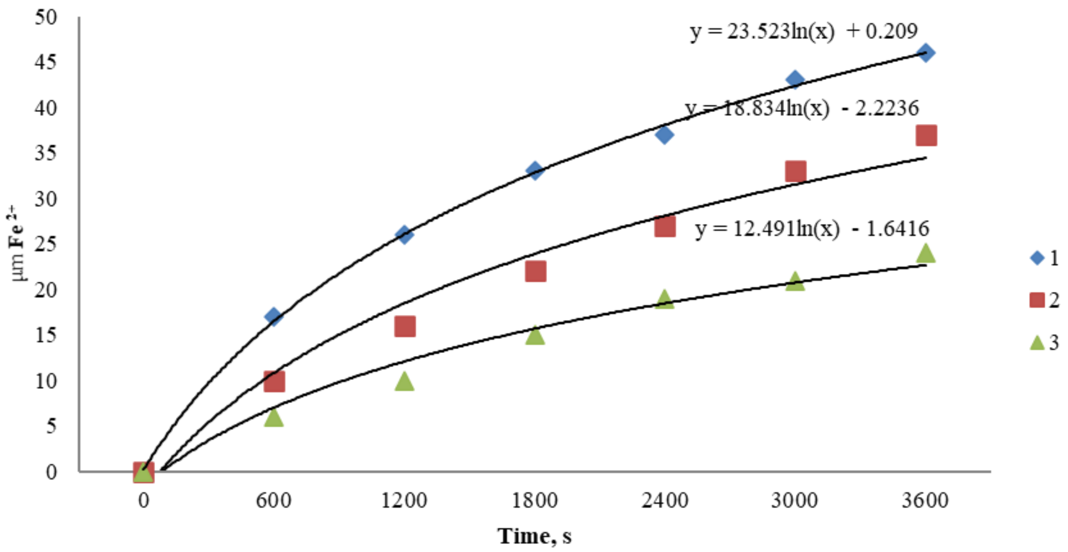

Fig. 6. Dynamics of reduction of trivalent iron with Emoxipin (in vitro)

increase in the concentration of pectin 10 times (from 0.1 to 1%) resulted in an increase in the content of reduced iron obtained 60 minutes after the start of incubation, an average of 4.1 times, and Emoxipine an average of 1.9 times.

Thus, in vitro, low-esterified pectin from red beet has more pronounced reducing properties than the antioxidant drug Emoxipine.

The obtained data suggest that this effect is partly due to the reducing properties of pectin and directly suppressing the mechanism of formation of lipid peroxidation products from unsaturated fatty acids. However, other mechanisms may be involved in the antioxidant effect of pectin, such as binding of heavy metal ions, including iron.

CONCLUSION

A mathematical model for describing the process of extracting pectin from plant raw materials under the complex influence of ultrasound and active mixing is proved, a criterion equation of the form: $Nu_D = 0{,}08Re^{0.5} \cdot Pr_D^{0.33} \cdot Te^{0.21} \cdot Us^{0.01}$ is proposed, which characterizes the intensity of extraction (the intensity of mass transfer in the solid-liquid system). By calculating the right part, the value of the Nusselt criterion (Nu_D) can be determined. Knowing the Nu_D, the mass transfer coefficient β can be determined. Then, using the mass transfer equation, the transferred amount of substance (pectin) to the extragent is calculated.

Provided reliable and adequate regression equation, which characterizes the most fully studied process: $Y=64.193+50.68 \cdot X_1+43.567 \cdot X_2+64.193 \cdot X_3-50.68 \cdot X_1^2+47.123 \cdot X_1 \cdot X_2-57.436X_1 \cdot X_3-43.567 \cdot X_2^2+53.88 \cdot X_2 \cdot X_3-64.193 \cdot X_3^2$ where Y - the yield of pectin; X_1 - the intensity of mixing; X_2 - intensity US; X_3 - duration of the extraction. Analyzing this equation, it can be noted that the intensity of ultrasound at selected intervals of variation should be reduced, the duration of extraction is at least 3 hours and up to 4 hours. Negative values of the double interaction coefficients indicate that a decrease in the influence of the second parameter (US intensity) leads to an increase in the influence of the other parameters (mixing intensity and extraction duration) and vice versa. The interpretation of the resulting model is presented as graphs of response surfaces.

The experiments performed indicate that the use of an ultrasonic emitter in the design of the plant raw material extractor, as well as a high-speed mixer, will significantly increase its efficiency by 19-21%.

In vitro, low-esterified pectin from red beet has more pronounced reducing properties than the antioxidant drug Emoxipine, which confirmed the possibility of using the resulting pectin extract as a dietary supplement.

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