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DRYING OF PROTEIN-CAROTINE-CONTAINING RAW MATERIALS BASED ON CARROT AND FABACEAE

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Abstract

The article presents the results of research on the preliminary preparation of protein-carotene-containing raw materials based on carrots and legumes for dehydration and its effect on the physical and chemical properties of the materials studied. The research showed that carrots without pre-treatment lose up to 44 % of carotenoids. The developed blanching regimes for certain types of raw materials made it possible to reduce these losses to 1 2%. The compositions were created by combining beans, peas, and oats at a temperature of 90 °C with carrots in a ratio of 1 part protein raw material or oats to 2 parts carrots before drying. This combination reduces carotenoid losses by 4.4–5.1 %. Energy-efficient drying modes for the studied raw materials have been developed, which depend on the temperature of the heat carrier and the moisture content of the material. This is demonstrated by theoretical calculations of the optimization criterion based on experimental data.. A comparison of the experimental τ_{exper} and the calculated τ_{teor} drying duration is presented, which shows that their error does not exceed 5 %. The process duration and drying rate are calculated and a graphical differentiation of generalized curves is presented, showing the difference in the kinetics and dynamics of drying in different parts of the process. Combining the drying curves obtained under different modes into one curve confirms that the generalized drying curve adequately describes the process and does not depend on the drying mode. The kinetics of heat transfer was studied with the determination of the specific heat flux density, which showed that a decrease in the moisture content of the material reduces the heat flux density from 1.4–1.8 to 0.05–0.07 W/m^2 and confirms the energy efficiency of the selected modes. Determination of the total content of carotenoids made it possible to prove that they are stored better in the compositions than in carrot powder after hygrothermal treatment by 6.3–9.6 %.

Keywords: carotenoids; carrot; drying; drying time; heat flux density.

СУШІННЯ БІЛКОВО-КАРОТИНОВМІСНОЇ СИРОВИНИ НА ОСНОВІ МОРКВИ ТА БОБОВИХ

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Анотація

У статті представлені результати досліджень попередньої підготовки білково-каротиновмісної сировини на основі моркви та бобових до зневоднення та її вплив на фізико-хімічні властивості досліджуваних матеріалів. Результати підготовки каротиновмісної сировини на основі моркви до сушіння показали, що морква без попередньої обробки втрачає до 44 % каротиноїдів. Розроблені режими бланшування моносировини дозволили зменшити ці втрати до 12 %. Створені композиції за рахунок поєднання квасолі, гороху, вівса за температури 90 °С з морквою в співвідношенні одна частина білкововмісної сировини чи вівса та дві частини моркви перед сушінням. Таке поєднання дає можливість зменшити втрати каротиноїдів на 4.4–5.1 %. На основі проведених досліджень розроблені енергоефективні режими сушіння досліджуваної сировини, які залежать від температури теплоносія та вологовмісту матеріалу. Як показали теоретичні розрахунки критерію оптимізації, обґрунтовані результатами експериментальних досліджень білково-каротиновмісної сировини. Зіставлені дослідна $\tau_{дос}$ та розрахункова $\tau_{роз}$ тривалості сушіння, та показано, що їх похибка не перевищує 5 %. Проведений розрахунок тривалості процесу й швидкості сушіння та представлене графічне диференціювання узагальнених кривих, які показують відмінність у кінетиці та динаміці сушіння в різних частинах процесу. Суміщення кривих сушіння, отриманих у різних режимах, в одну криву, підтверджує, що узагальнена крива сушіння адекватно описує процес і не залежить від режиму сушіння. Досліджена кінетика теплообміну з визначенням питомої густини теплового потоку, яка показала, що зменшення вологості матеріалу зменшує густину теплового потоку від 1.4–1.8 до 0.05–0.07 Вт/м^2 і підтверджує енергоефективність вибраних режимів. Визначення загального вмісту каротиноїдів дало змогу довести, що в композиціях вони зберігаються краще, ніж у морквяному порошку після гігротермічної обробки, на 6.3–9.6 %.

Ключові слова: каротиноїди; морква; сушіння; тривалість сушіння; густина теплового потоку.

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Introduction.

A carrot is a root vegetable, which is known for its high nutrient content and health benefits [1; 2]. It contains carotenoids, 95 % of which is β-carotene, a high content of antioxidants, flavonoids, vitamins and minerals, which give this product antioxidant, anticarcinogenic and immunostimulating properties [3].

Due to this, eating carrots in your daily diet increases immunity, strengthens the body's defenses, protects the skin from the harmful effects of the sun, due to the content of β-carotene, and also reduces the risk of cardiovascular diseases [4]. Numerous in vivo and in vitro studies have revealed numerous health benefits of carrot, including cholesterol-lowering, antidiabetic, antihypertensive, renoprotective, hepatoprotective effects, and facilitating the excretion of fats and bile by the liver.

Fresh carrots contain 88 % water, 10 % carbohydrates and 2 % protein with minerals and vitamins [5]. They also contain calcium, phosphorus, potassium, sodium, magnesium, iron, cobalt, zinc, as well as vitamins, mainly: A, B1, B2, B6, PP and folic acid [6; 7].

Storage of carotene-containing plant raw materials (carrot) in warehouses requires large areas and storage conditions, and during storage there are losses of carotenoids. Therefore, processing carrot into a dry food product is relevant [8, 9]. Most of the production of this vegetable is directed towards processing, including drying, which is usually an energy-intensive process [10–13].

As is known, carotenoids are best converted to retinol when the diet contains sufficient amounts of easily digestible protein and fat.

For the absorption and conversion of carotene into vitamin A, the form in which carotene and its related substances are introduced into the body is of great importance. Carotene, which is introduced into the body in the form of dehydrated herbal preparations or extracts, is absorbed much better if fats are consumed at the same time [14]. As a result, it is obviously rational to use dehydrated carotene-containing raw materials, together with fats.

Therefore, it was advisable to create such carotene-containing compositions that would contain a full range of carotenoids, lipids and proteins. Plants such as oats, peas and beans meet these requirements. Polyunsaturated fatty acids, which are part of cell membranes and other structural elements of plant tissues, perform a number of important functions in the body, including ensuring normal growth and metabolism, and the elasticity of blood vessels. Oats, peas and beans are also rich in protein, the content of which is up to 20–50 % [14].

In connection with the above, scientists from the Institute of Engineering Thermophysics of NAS of Ukraine developed a protein-carotene-containing composition based on carrot and fabaceae at the stage of preparing raw materials for drying. This combination makes it possible to combine carotenoids, proteins and fats in one product [15].

The main modern methods of drying carotene-containing raw materials are sublimation, convective and microwave drying, as well as hybrid methods: sublimation-convective, sublimation-microwave, convective-lyophilic or microwave-lyophilic. As a result of these studies, it was found that microwave-lyophilic drying makes it possible to obtain a high-quality product with a water activity similar ($p < 0.05$), however, the duration of such drying is 20 hours [6].

Another way to reduce the drying time of carrots is to use pre-treatment, which is described as treating carrots with ethanol before drying. As a result, scientists obtained a decrease in water content, mass loss and carotenoid concentration in the tissue, and the changes were more pronounced with increasing pre-treatment time and the use of ultrasound, especially when a frequency of 40 kHz was used. However, the tested samples practically did not change the drying time compared to the untreated sample, which was probably due to increased tissue shrinkage and partial destruction of the structure during drying. Dried, ethanol-pretreated carrot demonstrated increased rehydration rates (up to 19 %) and total carotenoid content (up to 135 mg/%). Scientists have stated that treatment with ethanol and ultrasound for a short time (up to 3 minutes) creates the possibility of obtaining dried carrots of a given quality that meets both the specific requirements of the consumer and the industry. However, this process is energy-intensive [16].

Another method of drying carrot slices is the method of using pre-treatment, which includes three freeze-thaw pre-treatments using different freezing methods: freezing at –80 °C, freezing at –25 °C, and vacuum freezing. The results showed that pre-treatment by freeze-thaw at different temperatures affected the water state of carrots, leading to varying degrees of moisture loss and a reduction in drying time from 14.3 % to 42.8 %.

These studies show that such pre-treatment increases the rehydration rate and crispiness of carrots. However, this method is quite energy-intensive [17].

Also, many studies on carrot drying are devoted to combined and other methods [11; 18–22].

Considering all the above-listed shortcomings, the development of new and improvement of existing methods of drying carrots is an actual task, with the main goal is to choose the optimal dehydration mode and preserve carotenoids as much as possible. One of the drying methods is the traditional convective method.

Experimental

Fresh, ripe carrots, peas, beans, and oatmeal were purchased at a supermarket in Kyiv and stored in the refrigerator. In preparation for the experiments, carrots were washed, peeled, and cut into shavings. Peas and beans were pre-prepared, namely fabaceae were poured with water at a temperature of 20 °C and left for 1 hour, after which they were boiled for 15 minutes. The oats were cooked for 15 minutes. For the research, protein-carotene-containing mixtures were created, namely pea-carrot, bean-carrot and oat-carrot by a ratio of 1 : 2.

The study of drying kinetics was carried out on an experimental convective drying stand, which is equipped with an automatic information processing and collection system, which allows for a more accurate characterization of the drying process with the construction of drying curves and drying rate [15]. The heat carrier temperature was determined using an anemometer, and the temperature using thermocouples. Experiments to study the drying kinetics were carried out under the following operating parameters: coolant velocity v = 1.5–3.5 m/s; layer height 10–20 mm; heat carrier temperature from 60 °C to 100 °C.

After the drying process, the moisture content of the material and the carotenoid content in the raw material after dehydration were investigated.

Carotenoids are found in the chromoplasts of cells and are surrounded by an aqueous environment. Therefore, the more finely ground the material, the more completely the carotenoids are extracted. Before extraction, the material is dehydrated, as carotenoids are fat-soluble substances. In this case, to determine the amount of carotenoids, it is necessary to take a sample of 0.1–2 g. The size of the sample is important when deciding on the method of separation and identification of carotenoids.

The sample is dehydrated with ethanol, thoroughly grinding it in a mortar to remove residual moisture.

To grind the raw starting product, the test material is ground in a mortar with a small amount of quartz sand until a homogeneous mass is obtained.

Quantitative determination of the carotenoids under study by changing the optical density using a spectrophotometer SF-26 gives fairly accurate results. The carotenoid content was determined by the formula:

$$\mathrm{X} = \frac{10 \cdot D \cdot V \cdot V_2}{E \cdot V_1 \cdot m} 100 \text{ , mg/100 g} \qquad (1)$$

where D – optical density of the test solution at a specified wavelength (β-carotene in hexane is determined at a wavelength of 453 nm);

E – extinction (specific absorption index at the same wavelength as that taken for β-carotene in hexane and equal to 2592);

100 – conversion factor per 100 g of analyzed sample;

V – total volume of extract, ml;

m – weight of the sample, g;

V_2 – cuvette volume, ml;

V_1 – extract volume for spectrophotometer.

When converting the carotenoid content or the sum of carotenoids to an absolutely dry substance, the moisture content of the studied material was taken into account.

The studies used the average value of three parallel experiments.

Results and discussion

As mentioned above, carotenoids are best converted to retinol when there is a sufficient amount of easily digestible protein and fat in the diet. Therefore, it was rational to create such carotene-containing compositions that would contain the full range of these compounds. Plants such as peas and beans meet these requirements.

The creation of a protein-carotene-containing composition directly affects the reduction of energy consumption for preparation for drying and the reduction of drying time, which is evident from the kinetics and drying rate curves. Accordingly, the preservation of carotenoids was determined using a standard method [23].

Hygrothermal treatment itself almost does not destroy carotenoids; these minimal losses are due to mechanical destruction of chromoplasts on the cut line of carrot parenchyma.

A different picture is observed during the drying of carotene-containing raw materials. Due to the action of lipoxygenase complex enzymes, we lose up to 44 % of carotenoids during drying of raw carrots. Steaming and water treatment of carrots for 2 min results in 13.5–19.8 % carotenoid loss during drying, indicating incomplete enzyme inactivation. The best results are obtained by blanching with steam for 3–5 minutes or with water for 3 minutes, but 11–12 % of carotenoids are destroyed during drying.

Combining carrot with fabaceae or oat with a material temperature of 90 °C before drying, preserves carotenoids during the drying process. For example, the loss of carotenoids in the pea-carrot mixture is 23.5 %, which is 1.87 times less, than in carrot (Table 1). From this it is obvious that carotenoids are stabilized by fat and proteins during grinding and mixing.

Fig. 1 presents the results of the preparation of antioxidant raw materials based on carrot before drying. The greatest losses of carotenoids, as can be seen from Fig. 1, without preparation of raw materials for drying, are 44 % (position 1). The existing hygrothermal treatment technology (position 2) results in losses of up to 25 %. The carrot blanching regimes we developed allowed us to reduce the loss of carotenoids during drying to 12 % (position 3). Blending of carotene-containing raw materials gives the best results, with losses of 5.1–4.4 % (position 4). Therefore, the optimal conditions for the preparation of carotene-containing raw materials are the blending of these raw materials.

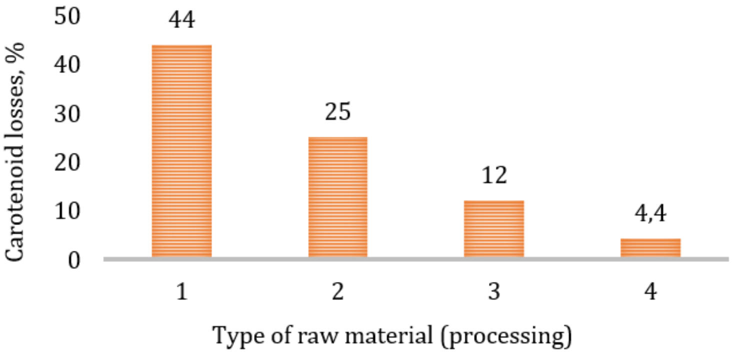


Fig. 1. Hygrothermal treatment of antioxidant raw materials:
1 – carrot without hygrothermal treatment; 2 – existing technology of hygrothermal treatment of carrot; 3 – hygrothermal treatment of mono raw materials; 4 - hygrothermal treatment of oat -carrot raw materials

As previously noted, peas and beans have anti-nutritional components that must be eliminated during pre-processing. Therefore, beans and peas, which have an ambient temperature of 98 °C, are mixed with chopped carrot, the temperature of the mixture is 60 °C, which is sufficient to inactivate lipoxygenase, while eliminating separate hygrothermal treatment of carrot.

Data on the preparation of antioxidant raw materials are presented in Table 1. The composition is left for 2–3 minutes, during the drying process the carotenoids are destroyed by 17.3–22.0 %.

Table 1

Preparation of raw materials for drying (hygrothermal treatment of fabaceae + mixing with fresh carrot)

Raw material	Hygrothermal treatment conditions		Carotenoid losses, %	
	Processing / holding time, min	temperature processing / composition, °C	during hydrothermal treatment	during drying at a temperature of 70 °C
Carrot	0	–	–	44
	2	(vapor 98 °C) / (water 98 °C)	0.8 / 1.0	19.8 / 13.5
	3	(vapor 98 °C) / (water 98 °C)	0.7 / 2.1	11.0 / 12.1
	5	(vapor 98 °C) / (water 98 °C)	0.6 / 2.5	11.5 / 17.4
	7	(vapor 98 °C) / (water 98 °C)	0.7 / 3.6	15.6 / 26.9
	10	(vapor 98 °C) / (water 98 °C)	0.8 / 3.8	25.5 / 35.4
Bean – carrot composition	0	–	–	27.5
	3 / 2	(water 98 °C) / 60	0.5	22.0
	3 / 3	(water 98 °C) / 60	0.2	17.3
	3 / 5	(water 98 °C) / 55	0.1	6.2
	3 / 7	(water 98 °C) / 54	0.3	4.4
	3 / 10	(water 98 °C) / 50	0.4	8.8

Continuation of table 1

Pea – carrot composition	0	–	–	23.5
	3 / 2	(water 98 °C) / 60	0.3	18.9
	3 / 3	(water 98 °C) / 60	0.1	15.6
	3 / 5	(water 98 °C) / 55	0.2	14.1
	3 / 7	(water 98 °C) / 54	0.3	3.5
	3 / 10	(water 98 °C) / 50	0.4	7.9
Oat – carrot composition	0	–	–	30.6
	2	(пара 98°C)	0.4	12.3
	3	(пара 98°C)	0.5	4.4
	5	(пара 98°C)	0.3	5.7
	7	(пара 98°C)	0.8	10.3
	10	(пара 98°C)	0.9	20.9

This time is not enough at this temperature to inactivate enzymes. The optimal technological process is at a composition temperature of 55.8 °C and a duration of 7 minutes.

Therefore, the optimal pre-treatment for carotene-containing raw materials is blending carrots with protein and fat-containing components and steaming for 3 min at an ambient temperature of 98 °C and holding the mixture for 7 min at a temperature of 55.8 °C. Using these developed modes, carotenoid losses are minimal and amount to 4.4 %. The full chemical composition of the studied raw material is given in [23].

Study of the kinetics of the raw material drying process

Dehydration of plant materials, as already emphasized, is one of the most important technological stages, which significantly determines the quality of the finished product [23; 24]. Combined plant compositions, as drying objects, are complex in their structure, physicochemical and biochemical composition. They combine the properties of grains, vegetables and fruits with a rich mineral and vitamin composition and high nutritional properties of vegetable protein. The vegetable protein content gives them special properties with preservation and better absorption of carotenoids. Studies of the kinetics of the drying process of antioxidant raw materials were carried out on such objects as pea-carrot, bean-carrot compositions.

Experimental studies were conducted on drying a pea-carrot composition in the range of coolant temperatures from 60 °C to 100 °C. The results of the research are presented in the form of curves of dehydration kinetics, drying rate and temperature curves shown in Fig. 2, 3. The change in the temperature of the mixture and the decrease in the moisture content of the material were determined automatically, so there are no points on the curves.

The duration of drying the material in the 100 °C is reduced by 2.25 times compared to the duration of the process at 60 °C (Fig. 2).

However, in the 100 °C coolant mode, a sharp increase in the material temperature is observed, and after the material reached a temperature of 80–90 °C, slight darkening and deterioration of the appearance occurred, which indicates a loss of product quality indicators. A combined analysis of the obtained data showed that the drying process of the binary mixture takes place in the second drying period (Fig. 3.*a*).

The drying curves of antioxidant raw materials have a form typical of colloidal capillary-porous materials.

As the evaporation zone deepens into the material, its surface temperature increases and the rate of moisture loss decreases. The drying rate curves show that with increasing coolant temperature, the dehydration intensity increases. As the heat carrier temperature increases, the maximum drying rate increases and shifts towards the lower moisture content of the material. So, at a heat temperature of 100 °C, the maximum speed is 10.5 %/min, which is 1.75 times greater than the maximum speed at a temperature of 60 °C.

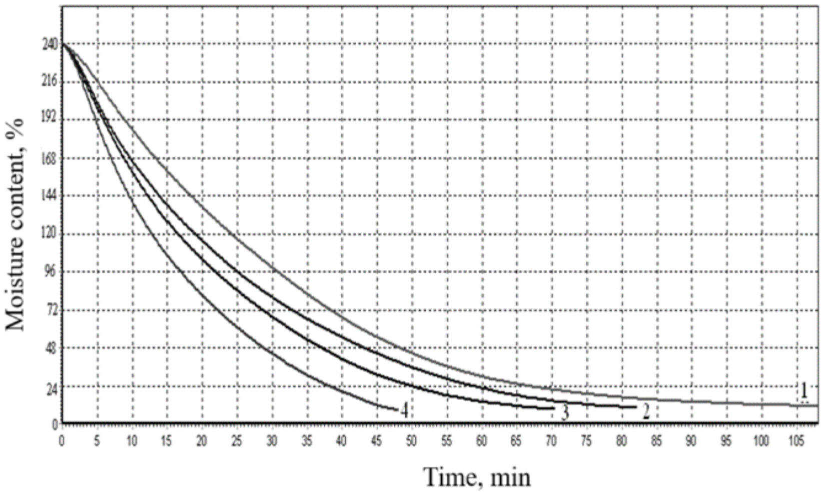
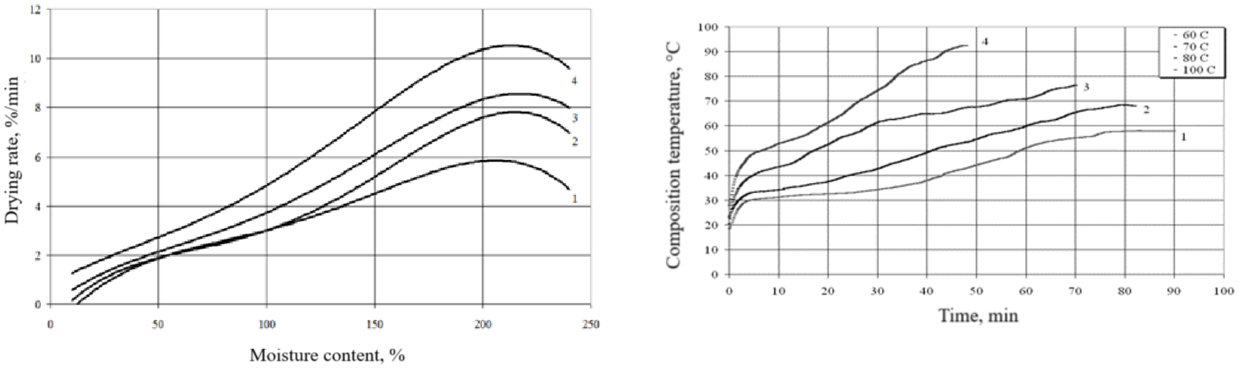


Fig. 2. The influence of the heat carrier temperature on the drying process of the pea-carrot composition (1:2) in a layer δ = 10 mm, *V* = 3.5 m/s; *W*$_{\text{final}}$ = 8 %; *d* = 10 g/kg dry air: 1 – 60 °C, 2 – 70 °C, 3 – 80 °C, 4 – 100 °C



a) *b)*

Fig. 3. Change in drying rate (*a*) and temperature in the middle of the layer (*b*) of a pea-carrot composition (1:2) as a function of the coolant temperature δ = 10 mm, *V* = 3,5 m/s; *W*$_{\text{final}}$ = 8 %; *d* = 10 g/kg dry air: 1 – 60 °C, 2 – 70 °C, 3 – 80 °C, 4 – 100 °C

Fig. 3.*b* shows the change in the temperature of the material in a 10 mm layer during the drying process, for which a chromel-copel thermocouple with a thickness of 0.25 mm was inserted into the middle of the central part of the sample. The intensity of heating of the material is higher at a temperature of 100 °C and at a duration of 48 min is 92 °C, which is 2.2 times higher, than at a temperature of 60 °C, which is 42 °C.

Table 2

The effect of heat carrier temperature on the preservation of carotenoids in a pea-carrot composition

Temperature, °C	Rate, m/s	Layer, mm	Carotenoids (% of preservation)
60	3,5	10	88,5
70	3,5	10	97,9
80	3,5	10	92,7
100	3,5	10	52

The choice of drying mode depends on the quality indicators of the pea-carrot composition, which was evaluated by the percentage of carotenoid preservation. As the conducted studies have shown, the temperature of the heat carrier affects the quality of the dried material (Table 2). At a temperature of 100 °C, carotenoids in the pea-carrot composition are preserved by only 52 %. A temperature of 60 °C also leads to loss of carotenoids. The optimal drying temperature of the pea-carrot composition is a heat carrier temperature of 70 °C, at which 97.9 % of carotenoids are preserved, as in pure carrot [25].

The influence of the drying rate on the kinetics of the drying process of the pea-carrot composition in the range of heat carrier rate from 1.5 to 3.5 m/s was studied at a carrier temperature of 70 °C, as the best for preserving carotenoids. The curves of dehydration kinetics, drying rate and temperature curves of the heat carrier rate are shown in Figures 4, 5, 6.

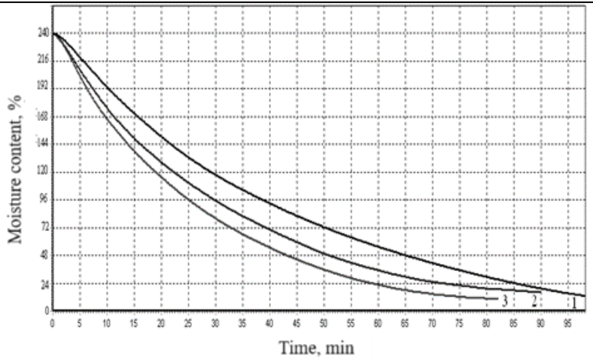


Fig. 4. The effect of the heat carrier rate on the drying process of the pea–carrot composition (1:2) in a layer δ = 10 mm, W_{final} = 8 %; t = 70 °C; *d* = 10 g/kg dry air: 1 – 1.5 m/s, 2 – 2.5 m/s, 3 – 3.5 m/s

Increasing the drying rate from 1.5 m/s to 3.5 m/s accelerates the drying process of the pea-carrot mixture and reduces the drying time by 15 %, which is significantly inferior to the influence of the heat carrier temperature (Fig. 4).

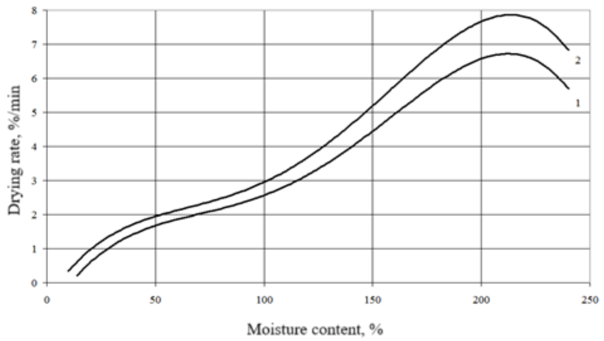


Fig. 5. The influence of the heat carrier rate on the drying process of pea–carrot composition (1:2) in a layer δ = 10 mm, W_{final} = 8 %; t = 70 °C; *d* = 10 g/kg dry air: 1 – 1.5 m/s, 2 – 2.5 m/s, 3 – 3.5 m/s

The drying process of the pea-carrot mixture takes place in a period of falling drying rate; with increasing heat carrier rate, the value of the maximum drying rate increases. Thus, increasing the heat carrier rate from 2.5 to 3.5 m/s increases the maximum speed value by 1.17 times (Fig. 5).

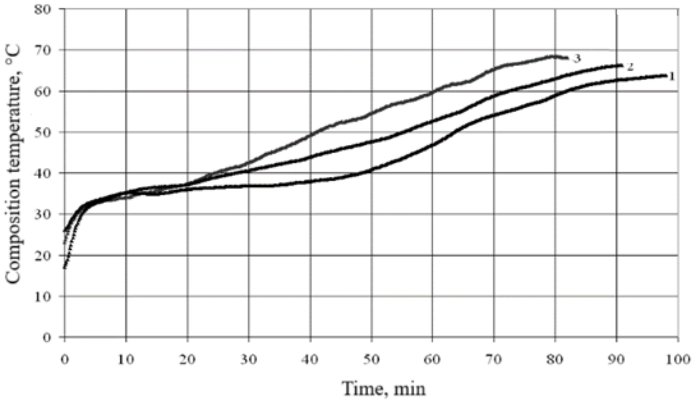


Figure 6. Temperature change in the middle of a layer δ = 10 mm of pea-carrot composition (1:2) from the rate of movement of the coolant W_{final} = 8 %; t = 70 °C; *d* = 10 g/kg dry air: 1 – 1.5 m/s, 2 – 2.5 m/s, 3 – 3.5 m/s

The presented curves of temperature changes in the middle of the material depending on the heat carrier rate show that within 20 minutes the change in the speed of the coolant almost does not change when the material is heated. Then the temperature in the middle of the layer increases significantly and by 82 min at a heat carrier rate of 3.5 m/s is 68 °C, which is 13 % higher than the material temperature at a heat carrier rate of 1.5 m/s (Fig. 6).

Changing the heat carrier rate not only intensifies the drying process by 15 %, but also increases the preservation of carotenoids by 7.2 % (Table 3). This can be explained by the fact that at a heat carrier rate of 3.5 m/s, due to the intensity of the process, minimal oxidation of carotenoids occurs.

At a heat carrier rate of 1.5 m/s, the process is slower and the carotenoids are partially oxidized. Based on the conducted research, the optimal heat carrier rate during drying of carotene-containing material is 3.5 m/s.

Table 3

The effect of heat carrier rate on the preservation of carotenoids in a pea-carrot composition

Rate, m/s	Temperature, °C	Layer, mm	Carotenoids (% preservation)
1.5	70	10	91.3
2.5	70	10	94.6
3.5	70	10	97.9

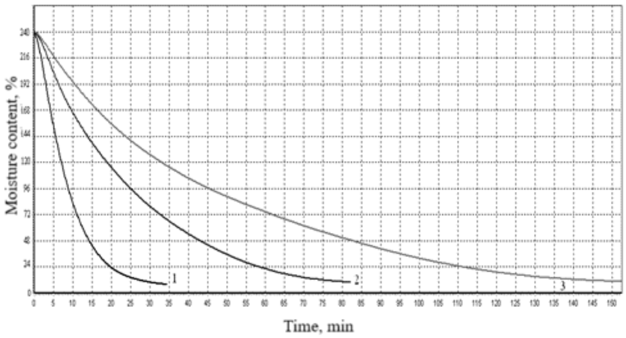


Fig. 7. The effect of the thickness of the layer of pea-carrot composition (1:2) on the drying process
W_{final} = 8 %; t = 70 °C; *V* = 3,5 m/s; *d* = 10 g/kg dry air:
1 – elementary layer, 2 – 10 mm, 3 – 20 mm

The next factor that affects the kinetics of the drying process is the thickness of the material layer (Fig. 7). The kinetics of the drying process were considered in the optimal drying mode: at a temperature of 70°C and a heat carrier rate of 3.5 m/s in a layer with a thickness of 2, 10 and 20 mm.

Increasing the layer thickness significantly increases the drying time of the pea-carrot composition, so drying the material with a layer thickness of 20 mm from a moisture content of 240 % to 10 % takes 152 minutes, which is 1.85 times longer than the drying time with a layer thickness of 10 mm and 4.32 times longer than in an elementary layer (Fig. 7).

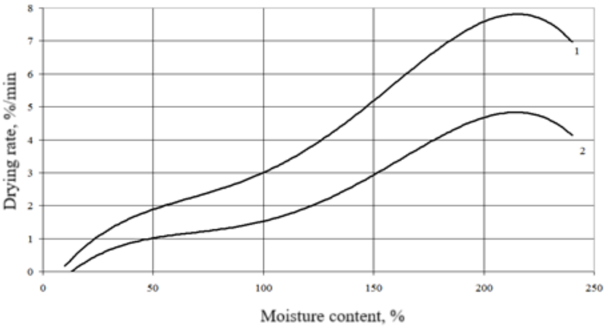


Fig. 8. Effect of the thickness of the pea-carrot composition layer (1:2) on the drying rate
W_{final} = 8 %; t = 70 °C; *V* = 3,5 m/s; *d* = 10 g/kg dry air:
1 – 10 mm, 2 – 20 mm

The drying process of the pea-carrot composition takes place in a period of decreasing drying rate. The maximum drying rate in a 10 mm layer is 7.8 %/min, which is 1.62 times greater than in a 20 mm layer (Fig. 8).

The presented curves of the change in material temperature from the layer thickness show that within 20 minutes the change in heat carrier rate almost does not change when the material is heated.

At the end of the drying process, the temperature of the material remains almost the same and is 68 °C, so in a 10 mm layer it occurs after a drying time of 82 minutes, and in a 20 mm layer after 152 minutes (Fig. 9).

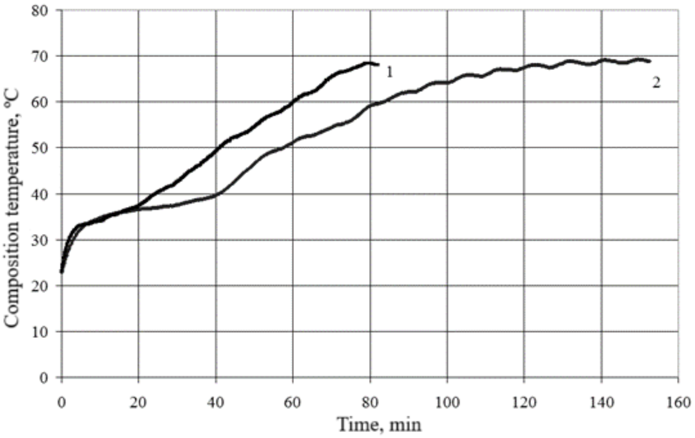


Figure 9. Temperature change of pea-carrot composition (1 : 2) depending on layer thickness W_{final} = 8 %; t = 70 °C; *d* = 10 g/kg dry air: 1 – 10 мм, 2 – 20 мм

Changing the thickness of the material layer has a minimal effect on the quality of the material (Table 4); with increasing material thickness, the duration of the process increases, which leads to partial losses of carotenoids. The smallest layer thickness of the material has the highest carotenoid levels, but based on the kinetics of the process and the requirements of the technology, we choose a layer thickness of 10 mm, as it ensures the intensity and productivity of the process.

The multifactorial experiment showed that the best quality drying indicators of the antioxidant composition were obtained under the following conditions: temperature 70 °C, heat carrier rate 3.5 m/s and material layer thickness 10 mm. Drying curves are characteristic of colloidal capillary-porous materials. Therefore, we conduct research on other antioxidant compositions based on carrots depending on the heat carrier temperature, where the greatest impact on quality indicators is observed.

With an increase in the heat carrier temperature from 60 to 100 °C, the drying time of the bean-carrot composition from the initial humidity of 190 % to the final humidity of 10 % decreases by 1.92 times.

The kinetics of the drying process of the bean-carrot composition under the influence of the heat carrier temperature is presented in Fig. 10.

Table 4

The influence of the thickness of the material layer on the preservation of carotenoids in the pea-carrot composition (1 : 2)

Layer, mm	Temperature, °C	Rate, m/s	Carotenoids (% preservation)
elementary layer	70	3.5	97.9
10 mm	70	3.5	96.4
20 mm	70	3.5	94.2

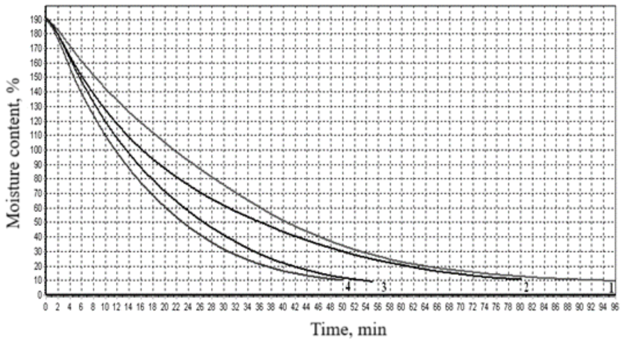


Fig. 10. The influence of the heat carrier temperature on the drying process of the bean-carrot composition (1:2) in a layer δ = 10 mm to W_{final} = 8 %; V = 3.5 m/s; d = 10 g/kg dry air:
1 – 60 °C, 2 – 70 ° C, 3 – 80 °C, 4 – 100 °C

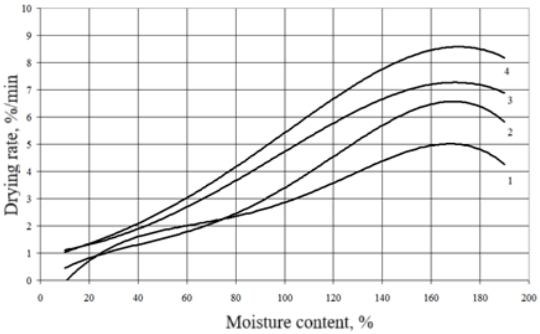


Fig. 11. The effect of the heat carrier temperature on the drying rate of the bean-carrot composition (1:2) in a layer δ = 10 mm to W_{final} = 8 %; V = 3.5 m/s; d = 10 g/kg dry air:
1 – 60 °C, 2 – 70 ° C, 3 – 80 °C, 4 – 100 °C

Table 5

The effect of heat carrier temperature on the preservation of carotenoids in a bean-carrot composition (1 : 2)

Temperature, °C	Rate, m/s	Layer, mm	Carotenoids (% preservation)
60	3.5	10	85.2
70	3.5	10	94.6
80	3.5	10	88.2
100	3.5	10	41.2

The maximum drying rate at a heat carrier temperature of 100 °C is 8.5 %/min, which is 1.7 times higher than the maximum rate at a temperature of 60 °C (Fig. 11).

The best preservation of carotenoids in the bean-carrot composition occurs at a temperature of 70 °C and is 94.6 % (Table 5)

Mixing fabaceae (peas and beans) with carrot and subsequent heat treatment showed high preservation of carotenoids with saturation of the resulting product with proteins and fat.

Drying at a temperature of 60–80 °C does not ensure high preservation of carotenoids and differs from a temperature of 70 °C by 6.4–9.4 % in a decreasing direction. At a drying temperature of 100 °C, the loss of carotenoids in the bean-carrot composition is 58.8 %.

Comparing the qualitative indicators of composite antioxidant compositions by carotenoid content, we can conclude that they retain carotenoids better than carrot powder after hygrothermal treatment by 6.3–9.6 % (Fig. 12).

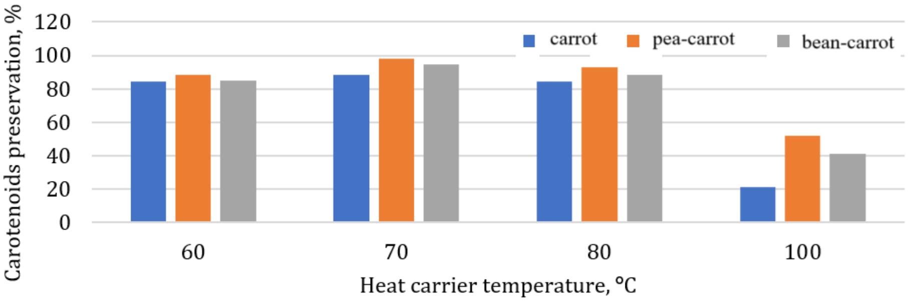


Fig. 12. Effect of heat carrier temperature on the preservation of carotenoids in carrot-based antioxidant compositions

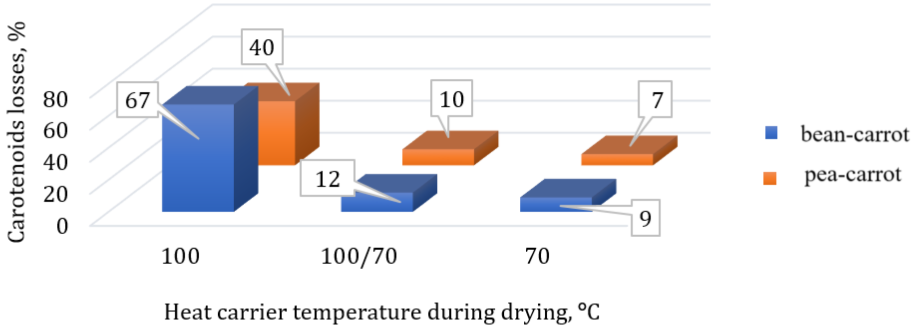


Fig. 13. Carotenoid losses depending on the drying mode and type of antioxidant composition

This can be explained by the fact that the content of protein and fat in the composite compositions ensures stabilization of carotenoids at optimal operating parameters by 93–96 %. The process parameters, as studies have shown, are the same for all carotene-containing products. Visually, you can observe the formation of a brown hue at a temperature of 100 °C – this is a characteristic sign of the formation of melanoids, which indicates the poor quality of the final product. The smallest losses of carotenoids are observed in the pea-carrot mixture at 40 %, the largest in the oat-carrot composition at 71 % (Fig. 13).

That is, in these compositions, except for the pea-carrot one, at a drying temperature of 100 °C only approximately 30% of carotenoids are preserved, everything else is lost.

The best results in preserving carotenoids were obtained at a drying temperature of 70 °C and amounted to 90–93 %. The stepwise drying mode ensures the preservation of carotenoids at the level of 87–90 %. At the same time, the antioxidant composition does not differ in color from the original raw material. Even a 3 % difference in carotenoid retention between the 70 and 100/70 °C regimes still favors the step regime due to the significant intensification of the drying process.

Calculation of the duration and rate drying processes of functional raw materials

The calculation of the kinetics of heat and moisture exchange during drying of functional products was performed using the method [24].

Analysis of many experimental data on the kinetics of drying of various materials (grain, vegetables, etc.) by various drying methods (convective, conductive, combined, infrared rays, in a fluidized bed), obtained by domestic and foreign researchers, allowed us to establish the following pattern: when drying a certain material, which has an initial humidity $W_{initial}$, in any drying mode, the independent value Nτ is preserved, which corresponds to a given intermediate humidity W.

In mathematical form, these patterns are represented by the expression:

$$N_1\tau_1 = N_2\tau_2 = N_n\tau_n = (N\tau)_W = const, \qquad (2)$$

where: $N_1, N_2, \ldots N_n$ – drying rate in the first period (in the absence of the first period - maximum drying speed) at different modes;

τ_1, τ_2, τ_n – intermediate drying time during which the humidity changes from the initial humidity $W_{initial}$ to the humidity W.

The variable $N\tau$ is a stable complex of values characteristic of the drying process. Therefore, in accordance with the foundations of similarity theory and dimensional analysis [12], the value $N\tau$ was called a generalized variable or generalized drying time.

In the partial case for the first drying period:

$$(N_\tau)_W = W_{initial} - W \qquad (3)$$

In general, for the second drying period:

$$(N_\tau)_W = W_{initial} - W + W_x = const, \qquad (4)$$

where Wx – a quantity that depends on the properties of the material, is determined by experiment.

Operating with generalized drying time gives the study of the drying process a generalized character. The same value can be obtained as a result of numerous different combinations of N and τ, that is, a fixed value of $N\tau$ corresponds not to one specific set of primary quantities, but to a many similar sets. Accordingly, when studying the drying process using $N\tau$, not a single partial case is analyzed, but numerous of different drying cases, united by some generalization of process parameters. The larger the value of N, the shorter the drying time τ required to reach a given humidity W, but according to (3) or (4) for all possible N, for this W, the value of $N\tau$ remains constant.

From the above, it follows that if we plot the generalizing time $N\tau$ on the abscissa axis, and the value of the intermediate humidity W on the ordinate axis, then all the experimental drying curves of this material, obtained at the same initial humidity $W_{initial}$, but under different modes (family of curves), transferred to the new coordinate system W – $N\tau$, are combined into a single curve, called the generalized drying kinetics curve.

Fig. 14 presents the drying curves of antioxidant raw materials based on carrot. When constructing these curves, data obtained in experiments with different temperature modes were generalized, taking into account the rate and moisture content of the heat carrier and the material layer.

From Fig. 14 it is seen, that at high material humidity the points corresponding to different drying modes are located near the generalized curve. As the current humidity decreases, the scatter of points increases, but is within the error range.

Generalized drying kinetic curves of antioxidant mixtures allow us to determine the relative drying coefficients of the second period. The relative drying coefficient χ is determined only by the formula for the relationship between moisture and the material, its structure, and density, and does not depend on the processing mode.

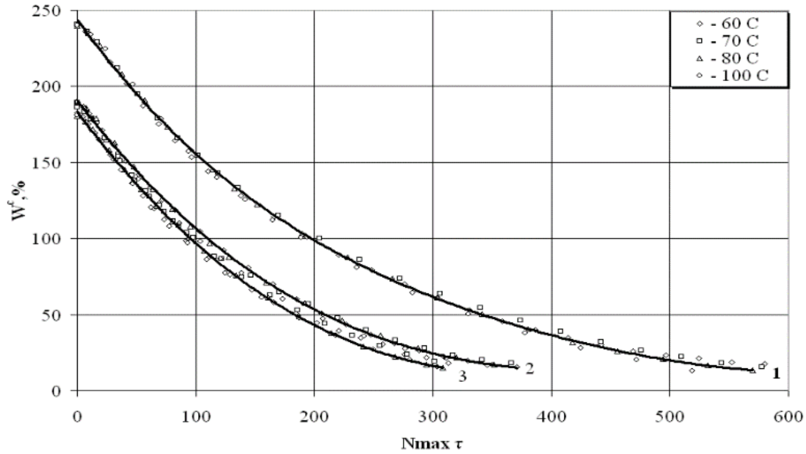


Fig. 14. Generalized curves of drying kinetics of antioxidant compositions depending on the heat carrier temperature: 1 – pea-carrot; 2 – bean-carrot, 3 – oat-carrot

The relative drying coefficients are determined from the generalized curve using the following expressions:

$$\chi_1 = \frac{\lg(W\kappa_1 - Wp) - \lg(W\kappa_2 - Wp)}{N \max \tau_1} \quad (5)$$

$$\chi_2 = \frac{\lg(W\kappa_2 - Wp) - \lg(W\kappa_3 - Wp)}{N \max \tau_2} \quad (6)$$

$$\chi_3 = \frac{\lg(W\kappa_3 - Wp) - \lg(W\kappa_4 - Wp)}{N \max \tau_3} \quad (7)$$

$$\chi_4 = \frac{\lg(W\kappa_4 - Wp) - \lg(W\kappa - Wp)}{N \max \tau_4} \quad (8)$$

where $W_{initial}$ – initial moisture content of the material, %;

$W\kappa_1, W\kappa_2, W\kappa_3, W\kappa_4$ – moisture content of the material at points К_1, К_2, К_3, К_4;

Wp – equilibrium moisture content of the material, %;

$W\kappa$ - final moisture content of the material, %;

$\tau_1, \tau_2, \tau_3, \tau_4$ – duration of the first, second, third and fourth parts of the drying process, min.

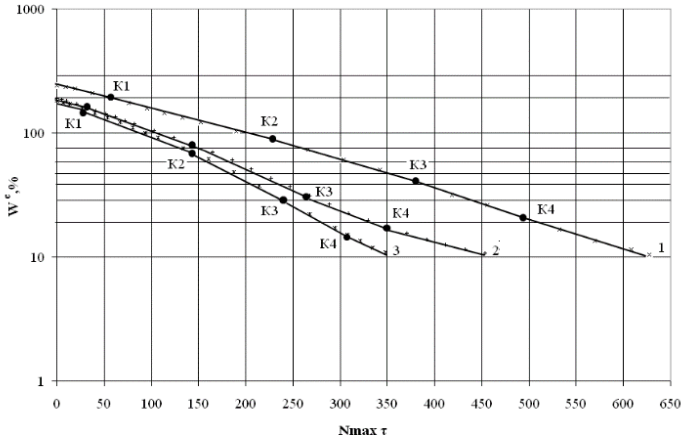


**Figure 15. Generalized drying curves of antioxidant compositions in a semi-logarithmic coordinate system
1 – pea-carrot; 2 – bean-carrot; 3 – oat-carrot**

The constructed generalized drying curves of antioxidant compositions show that the drying process in the second period (Fig. 15).

The curves are represented by broken lines, which indicates the complex nature of the second period.

The second period consists of four drying parts, each of which is characterized by its own drying coefficient, which is calculated using formulas (4–7) and entered into the table 5.

When calculating the relative drying coefficients for the above antioxidant compositions, the equilibrium humidity of the heat carrier parameters for d = 10 g/kg of dry air, at a temperature of 20 °C (according to our own research) is: for the pea-carrot composition – 9.30 %; for the bean-carrot composition – 9.18 %.

It is known that the drying rate in each part of a particular period is represented by a straight line in a semi-logarithmic coordinate system, that is the real drying rate curve is replaced by a broken line curve.

Fig. 16 shows that the generalized drying rate curves are represented by smooth sloping curves. In order to describe the dependences of N^* on W, the generalized drying rate curves are plotted in semi-logarithmic coordinates.

Table 5

Relative drying coefficients of antioxidant raw materials

№	Title of composition	Critical moisture content range, %	The value of relative drying coefficients			
			χ_1	χ_2	χ_3	χ_4
1.	Pea–carrot	190–80	0.00238			
		80–40		0.00237		
		40–20			0.00395	
		20–10				0.00557
2.	Bean–carrot	171–80	0.00312			
		80–31		0.00414		
		31–17			0.00529	
		17–10				0.00652
3.	Oat–carrot	158–75	0.0029			
		75–30		0.00518		
		30–15			0.00789	
		15–10				0.01272

By performing graphical differentiation of the generalized drying kinetics curves presented in Fig. 16, generalized drying rates were obtained fig. 17, which are determined by the following expression:

$$N^* = \left|\frac{dW}{d\tau}\right| \div \mathrm{N} = \frac{dW}{Nd\tau} = tg(W, N\tau) = f(W) \tag{9}$$

The value of N^* does not depend on the drying modes and for specific materials with given drying methods is a function of moisture content.

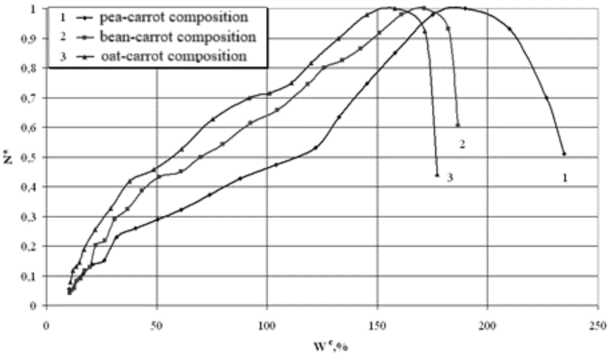


Fig. 16. Generalized drying rate curves of antioxidant compositions:
1 – pea-carrot; 2 – bean-carrot; 3 – oat-carrot

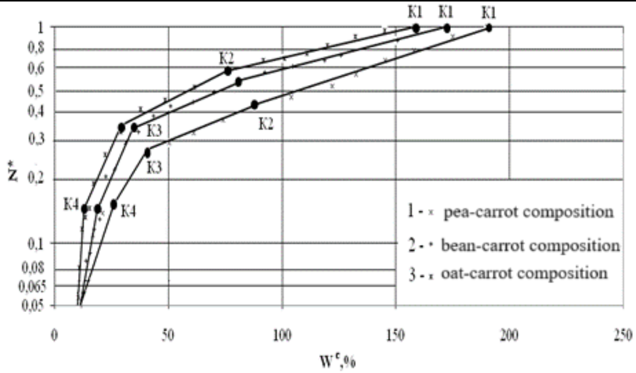


Fig. 17. Generalized drying rate curves of antioxidant mixtures in semi-logarithmic coordinates
1 – pea-carrot; 2 – bean-carrot, 3 – oat-carrot

In semi-logarithmic coordinates, generalized drying rates are represented by broken lines consisting of four straight lines (Fig. 17). The law of change when moving from one part to the second part changes, indicating a difference in the kinetics and dynamics of drying in different parts of the drying process.

The values of N^* in different parts of the drying process in the second period, excluding the material warming-up period, are determined by the following empirical relationships presented in Table 6.

Table 6

The value of the generalized drying rate of protein-carotene-containing compositions

№	Title of composition	Critical moisture content range, %	The value of the generalized drying rate
1.	Pea - carrot	190 – 80	$N^* = 0.1762e^{0,0093W}$
		80 – 40	$N^* = 0.1867e^{0,0089W}$
		40 – 20	$N^* = 0.0657e^{0,0352W}$
		20 – 10	$N^* = 0.0209e^{0,0934W}$
2.	Bean-carrot	171 – 80	$N^* = 0.3322e^{0,0064W}$
		80 – 31	$N^* = 0.2125e^{0,0123W}$
		31 – 17	$N^* = 0.0376e^{0,0669W}$
		17 – 10	$N^* = 0.0104e^{0,1406W}$
3.	Oat-carrot	158 – 75	$N^* = 0,4003e^{0,0059W}$
		75 – 30	$N^* = 0,239e^{0,0013W}$
		30 – 15	$N^* = 0,0672e^{0,0555W}$
		15 – 10	$N^* = 0,0208e^{0,1326W}$

Total theoretical duration of the drying process τ_T (excluding heating-up period) consists of the drying duration in the first period τ_1, in 1-st τ_2, 2-st τ_3, 3-st τ_4 and 4-st τ_5 parts of the second period:

$$\tau_T = \tau_I + \tau_1 + \tau_2 + \tau_3 + \tau_4 \tag{10}$$

The drying duration in the first period is:

$$\tau_I = \frac{Wn - W\kappa_1}{N} \tag{11}$$

Drying duration in the 1st part of the second period:

$$\tau_1 = \frac{1}{\chi_1 N} \lg \frac{W\kappa_1 - Wp}{W\kappa_2 - Wp} \tag{12}$$

Drying duration in the 2nd part of the second period:

$$\tau_2 = \frac{1}{\chi_2 N} \lg \frac{W\kappa_2 - Wp}{W\kappa_3 - Wp} \tag{13}$$

Drying duration in the 3rd part of the second period:

$$\tau_3 = \frac{1}{\chi_3 N} \lg \frac{W\kappa_3 - Wp}{W\kappa_4 - Wp} \tag{14}$$

Drying duration in the 4th part of the second period:

$$\tau_4 = \frac{1}{\chi_4 N} \lg \frac{W\kappa_4 - Wp}{W\kappa - Wp} \tag{15}$$

Total process duration:

$$\tau_T = \frac{1}{N}(Wn - W\kappa_1 + \frac{1}{\chi_1}\lg\frac{W\kappa_1 - Wp}{W\kappa_2 - Wp} + \frac{1}{\chi_2}\lg\frac{W\kappa_2 - Wp}{W\kappa_3 - Wp} + \frac{1}{\chi_3}\lg\frac{W\kappa_3 - Wp}{W\kappa_4 - Wp} + \frac{1}{\chi_4}\lg\frac{W\kappa_4 - Wp}{W\kappa - Wp}) \qquad (16)$$

In formula (25) the values of critical moisture content Wk_1, Wk_2, Wk_3, Wk_4, Wk and relative coefficients $\chi_1, \chi_2, \chi_3, \chi_4$ are found directly from the generalized drying curve in semi-logarithmic coordinates.

Table 7

Duration of the drying process of antioxidant raw materials

№	Title of composition	Calculated duration of the drying process, min
1.	Pea - carrot	$\tau = \frac{640}{N}$
2.	Bean-carrot	$\tau = \frac{442}{N}$
3.	Oat-carrot	$\tau = \frac{349}{N}$

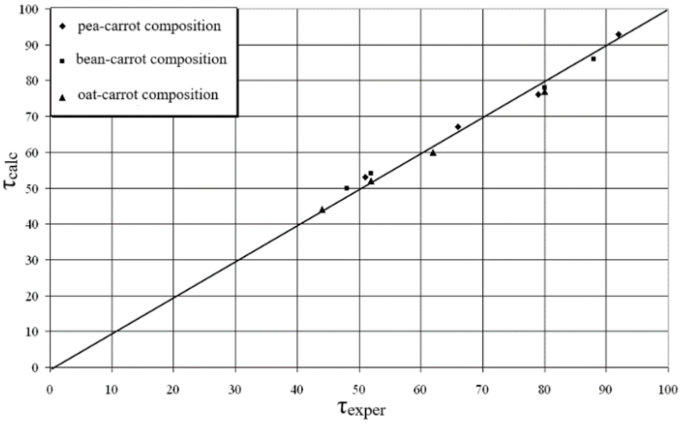


Fig. 18. Comparison of experimental and calculated drying times of antioxidant raw materials on a convective stand

The total drying time of antioxidant raw materials is calculated using formula (16) and is summarized in the table 7.

Fig. 18 shows a comparison of the experimental τ_{exper} and the calculated τ_{calc} duration of drying of antioxidant raw materials at different heat carrier temperatures (60, 70, 80, 100 °C).

The value of τ_{calc} is calculated by formula (16) and is approximate to the experimental value. The fault between the experimental and calculated values does not exceed 5 %.

Research of heat and mass transfer processes during drying of functional raw materials

The kinetics of heat transfer during drying can be fully revealed from the kinetics of moisture transfer.

The heat supplied to the material is spent on heating the material and evaporating moisture.

The density of the heat flux spent on evaporation is calculated based on the intensity of moisture exchange. $m(\tau)$ from the expression:

$$q_{evap} = rm(\tau) = rg\frac{d\overline{W}}{d\tau} \qquad (17)$$

In this case, we do not take into account the shrinkage of the material.

The heat flux density for heating the material is determined by the ratio:

$$q_{heat} = cg\frac{d\overline{t}}{d\tau} \qquad (18)$$

where c – heat capacity of the antioxidant composition.

In accordance with the law of conservation of energy, the specific heat flux per unit surface area of the body is equal to:

$$q(\tau) = rg\frac{d\overline{W}}{d\tau} + \overline{c}g\frac{d\overline{t}}{d\tau} = gr\frac{d\overline{W}}{d\tau}\left[1 + \frac{\overline{c}}{r}\frac{d\overline{t}}{d\overline{W}}\right] \qquad (19)$$

The heat flux density increases as the material is heated to its maximum value. When moisture is removed from a material, the heat flux density decreases. Moreover, the largest decrease corresponds to the most intensive drying mode (Fig. 19).

That is, it confirms the need to reduce the temperature of the coolant at the final stage of the drying process and the use of stepwise drying modes to intensify the process.

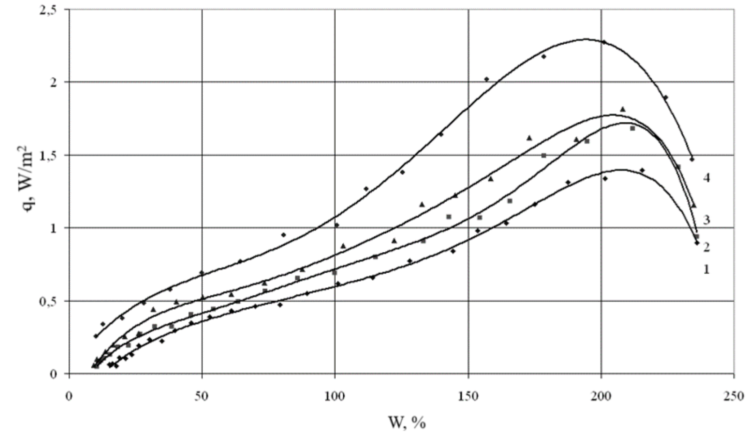


Fig. 19. Dependence of heat flux density on moisture content during drying of pea-carrot mixture at heat temperature 1 – 60 °C; 2 – 70 °C; 3 – 80 °C; 4 – 100 °C

Value of quantity $\frac{d\overline{W}}{d\tau}$ determines the change in the average temperature of the dried material per unit change in its average humidity over an infinitely small period of time and is called the temperature coefficient of drying:

$$b = \frac{d\bar{t}}{d\overline{W}} \tag{20}$$

Quantity b is a function of the integral humidity $b = f(\overline{W})$.

General variable $b\frac{\bar{c}}{r}$, as can be seen from the equation is an integral characteristic of the kinetics of the drying process. It determines the ratio of the amount of heat required to heat the material during drying and to evaporate moisture over an infinitely small period of time. This is the main criterion for optimizing drying *(Rb)* [26; 27]:

$$Rb = b\frac{\bar{c}}{r} = \frac{\bar{c}}{r}\left(\frac{d\bar{t}}{d\overline{W}}\right) \tag{21}$$

Fig. 20 shows that the drying optimization criterion depends on the heat carrier temperature and moisture content.

At the beginning of the drying process, the moisture content decreases to point K1, the value of the drying optimization criterion (*Rb*) decreases, that is heat during drying is spent more on evaporating moisture from the material than on heating it.

When reaching the critical moisture content W_K = 190–200 %, the drying optimization criterion (*Rb*) begins to increase, which indicates that most of the heat is spent on heating the material, and not on evaporating moisture from it (section *K1–K2*). When reaching the critical moisture content W_K = 80–89 %, the drying optimization criterion (*Rb*) increases sharply, which means that more heat is spent on heating the material. The nature of the change in the drying optimization criterion (*Rb*), as seen from the segment *K2–K3*, proves the need to implement the optimal mode for protein-carotene-containing raw materials and its application in a convective experimental industrial dryer.

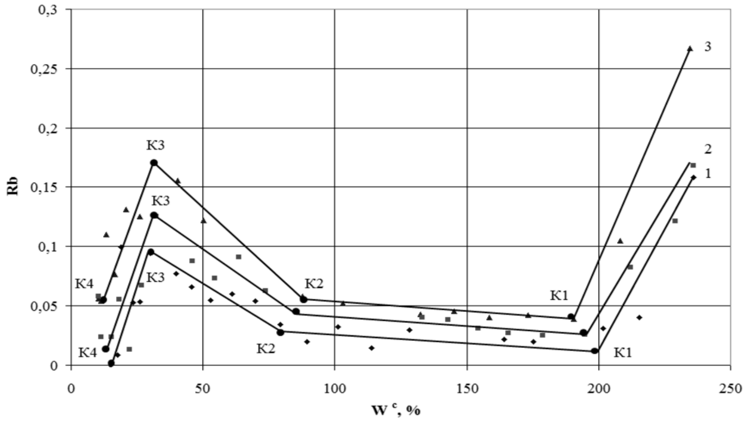


Fig. 20. Dependence of the drying optimization criterion (Rb) on the moisture content during drying of a pea-carrot composition at the heat temperature: 1 – 60 °C; 2 – 70 °C; 3 – 80 °C

A strong decrease in the drying optimization criterion (*Rb*) in the *K3–K4* section when the material reaches a moisture content of 40–20 % indicates that the material is almost completely heated, and the heat is spent on removing the most strongly bound moisture. The value of the drying optimization criterion (*Rb*) depends on the temperature coefficient of drying, the specific heat capacity of the wet material and the specific heat of evaporation, and accordingly on the form of the moisture bond with the material. Therefore, it makes no sense to maintain a high coolant temperature at the last stage of the dehydration process. Processing of experimental data proved that the drying optimization criterion (*Rb*) is determined by the thermal drying mode.

Conclusions

1. As a result of experimental studies, optimal drying modes for functional antioxidant raw materials have been determined.

2. The optimal dehydration temperature of protein-carotene-containing raw materials, at which the preservation of carotene is 80 %, has been experimentally established.

3. Losses of biologically active substances in compositions during drying are 10–20 % less than in single raw materials.

4. Calculated intensity and duration of dehydration of antioxidant raw materials.

5. Calculated heat flux density, which is spent on moisture evaporation depending on the evaporation intensity and moisture content of the material.

6. The dependence of the drying optimization criterion on the moisture content of the material was investigated, which substantiates the effectiveness of the proposed effective drying modes.

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