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RESEARCH OF THE KINETICS OF THE DRYING PROCESS OF COMBINED PLANT MATERIALS

Petrova Z.O., Doctor of Technical Sciences, Chief Researcher,
Slobodianiuk K.S., Ph.D., Senior Researcher, Samoilenko K.M., Ph.D., Senior Researcher,
Vishnevsky V .M., graduate student, Grakov O.P., graduate student
Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine, Kyiv

Abstract. *The general trend of energy consumption, which leads to an increase in the amount of energy consumed in the world, has shown that its cost is constantly increasing, and the shortage of energy carriers is increasing. So, the problem of creating and large-scale implementation of modern energy-efficient heat-technologies, which ensure the reduction of energy consumption and the maximum preservation of the high quality of the dehydrated product, is relevant today.*

In order to solve the above-mentioned problem, this work has developed an innovative pre-treatment of combined plant materials. A study of pH results for different ratios of red beetroot with rhubarb/tomato is presented. We managed to obtain the most optimal content of components in the red beetroot:rhubarb mixture as 2:1, with a pH value of 3.75, and betanin in the studied material after drying remains at the level of 96.5% for red beetroot:tomato - 3:1, in which pH is 3.9, and betanin is 94.7%. Also, with the preservation of earnings and increasing the functionality of the phytoestrogen properties of plant raw materials, the conditions for the stabilization of plant ingredients have been developed. Mixtures of plant materials with different ratios of initial components of plant origin were created and optimal drying modes were developed.

The kinetics of the drying process of combined plant materials with their preliminary preparation was experimentally investigated.

On the basis of the obtained data on the change in the nature of the Rebinder number depending on the humidity, the combined plant material and the temperature of the heat carrier, staged drying regimes were developed.

The theoretical processing of the obtained experimental data on the red beetroot:tomato mixture was performed according to the method of V.A. Danilov. The generalized drying kinetics curves of the red beetroot:tomato mixture coincide with the fast drying regimes.

The duration of the drying process of the soybean:spinach mixture on the experimental convective stand was calculated according to the method of V.V. Krasnikov. The generalized curve of the drying kinetics of the soybean:spinach mixture made it possible to apply the relative drying coefficients. And it became possible to calculate the total drying time of the soybean:spinach mixture. The deviation of the calculated value from the experimental duration of drying does not exceed 5%.

Keywords: heat and mass transfer, drying kinetics, drying rate, Rebinder, combined functional materials.

Statement of the problem. An analysis of modern scientific sources confirmed the need to create and develop highly efficient heat-technologies that ensure minimal energy consumption and high quality of the material [1-3]. Drying processes in the world consume from 10 to 12% of all energy [4]. They are determined by the processes of heat and mass transfer. The efficiency of drying and the economy of the use of material and energy resources depend on their intensity [5].

The main problems when using the convective drying method are: significant heat loss with the spent drying agent; insufficient intensity of the dehumidification process when using low drying temperatures; Dependence of the efficiency of the dryer on the humidity of the atmospheric air [6]. The solution to these problems is offered through: utilization of the heat that comes with the spent drying agent; forced drying of the drying agent in order to intensify mass transfer; controlled conditions of the dewatering process [7].

Increasing the energy efficiency of heat and mass transfer for drying combined functional materials (functional materials of plant origin are thermolabile colloidal capillary-porous materials) in combination can positively affect the economy [7].

Research objects and preparation of combined functional materials for drying. Drying is one of the main methods of processing functional plant raw materials [8]. The quality and biological value of dried products depends on the preparation of raw materials for drying, the temperature regime of drying, the duration of thermal exposure to the product. Some dried products are classified as functional foods (according to the classification of the main plant functional ingredients by Doctor of Technical Sciences Petrova Zh.A.), such as antioxidant based on red beetroot and phytoestrogenic based on soy [4].

The main raw material, with a high content of betanine and antioxidant properties, is red beetroot. Natural pigments refer to natural food ingredients and dyes, which have attracted considerable attention as antioxidants, have a beneficial effect on human health and disease prevention [5].

Beetroot betanin is one of the strongest antioxidants and, when dried, is destroyed not only by the temperature of the coolant, but also by the pH of the medium. For complete drying of betanine, an acidic environment is needed. The pH value of red beetroots approaches neutral, so vegetable raw materials with a high content of organic acids were added to it to obtain the optimal pH. The pH was studied for various ratios of red beetroot and rhubarb or tomato. We managed to obtain the most optimal ratio of red beetroot-rhubarb (2:1), while the pH value is at which pH is 3.75, and betanin in the test material after drying remains at the level of 96.5 % for red beetroot-tomato - 3:1, at which pH is 3.9 and betanin is 94.7 %.

Soy is considered the main supplier of phytoestrogens and contains a large amount of protein and fat. Soybeans and other legumes containing proteins are considered an environmentally friendly source of protein [9].

In order to preserve and increase the functionality of the phytoestrogenic properties of plant raw materials, the conditions for stabilizing herbal ingredients were developed. Which provide for the preliminary hydrothermal treatment of soybeans and its blending to prevent enzymatic and non-enzymatic browning during the temperature exposure during the drying period.

We have improved the preliminary hydrothermal preparation of soybeans for drying [10], which was developed by us earlier [11]. This made it possible to inactivate anti-food components in soy and make the process of heat and moisture transfer more intense.

Soy contains a high amount of fats, which, after grinding the pre-treated hydrothermally, are oxidized [12]. Sweet potato and spinach carotenoids are natural fat stabilizers [12]. Based on these properties of the material after hydrothermal treatment, soybeans were blended with carotene-containing vegetables such as spinach and sweet potato [12].

After the research on the preliminary preparation of raw materials, combined functional materials were developed: soy-spinach and soy-sweet potato mixtures, the soy-vegetable ratio was 1:1.

Preliminary preparation of combined functional materials (antioxidant and phytoestrogenic) further reduced the overall duration of the process.

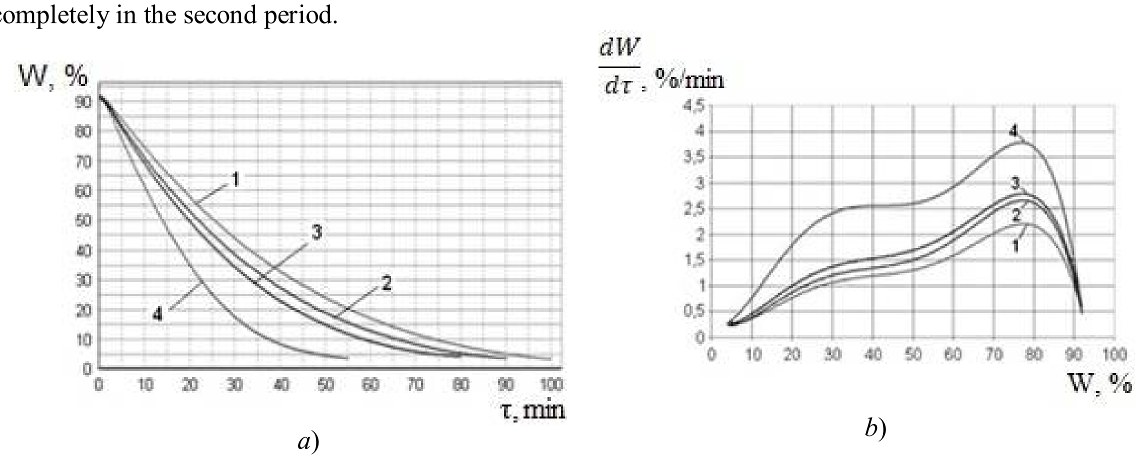
Research of the kinetics of convective drying of combined functional materials. At the Institute of Technical Thermal Physics of the National Academy of Sciences of Ukraine, studies were carried out on the processes of convective drying of combined functional materials (antioxidant and phytoestrogenic) on an experimental convective stand [9]. The stand is technically provided with automatic collection and processing of information by the application program «Sooshka», developed by the staff of the Institute.

Research results in the form of drying curves $W = f(\tau)$ and drying speed $\frac{dW}{dt} = f(W)$ shown in the figs. 1, 2, 3, 4 and 6.

Our previous studies [5] of the kinetics of drying the antioxidant red beetroot-tomato mixture, where the red beetroot is cut into a plate and chips, confirmed the assumption that when cutting the red beetroot with chips, the drying process is intensified by 1.4 times compared to the plate [5]. This was also confirmed by the drying rate curves [5]. Therefore, further studies were carried out with cutting red beetroots into shavings.

The effect of the coolant temperature on the drying kinetics of the red beetroot-tomato mixture (component ratio 3:1) was studied in a wide temperature range (Fig. 1, a). With an increase in the temperature of the coolant, the intensity of the drying process of the composition increases. From fig. 1, a, it can be seen that at the coolant temperature 60 °C the duration of the process is 100 min, which is 1.8 times longer than at a temperature 100 °C [13].

Accordingly, from fig. 1, b, the maximum drying rate is traced at the temperature of the coolant 100 °C – 3,8 %/min (curve 4), and the minimum - 2,2 %/min at heat carrier temperature 60 °C (curve 1). The shape of the drying rate curves is typical for colloidal capillary-porous materials and the main dehydration process takes place completely in the second period.



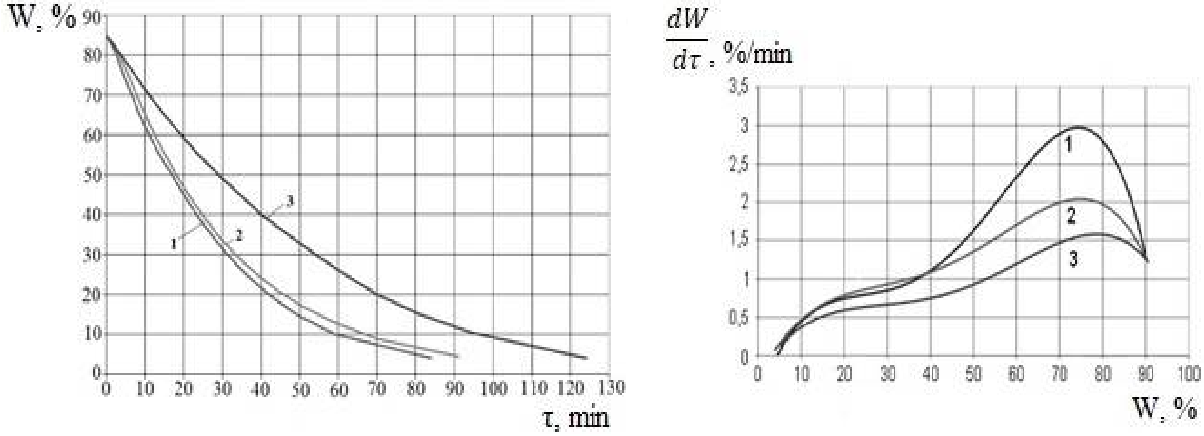
a) *b*)

1 – 60 °C; 2 – 70 °C; 3 – 80 °C; 4 – 100 °C.

Fig. 1 – Kinetics (a) and velocity (b) of drying the red beetroot-tomato mixture depending on the temperature of the coolant (regime parameters: v = 3,5 m/sec, δ = 10 mm, d = 10 g/kg dry air)

The influence of the mixture components on the kinetics of the drying process was studied (fig. 2). The mixture (fig. 2, a curve 1) reaches the final moisture content 1.5 times faster than red beetroot (fig. 2, a curve 3).

On the curves of the drying rate of the components and the mixture itself (fig. 2, b) it can be seen that the maximum drying rate in the beetroot-tomato mixture is 3.0% / min, the drying rate of red beetroot is 2.1%, the lowest drying rate in tomato – 1.6%/min. This is due to the influence of tomato organic acids on the cell membrane of red beetroot and, possibly, a change in the ratio of free and bound moisture.



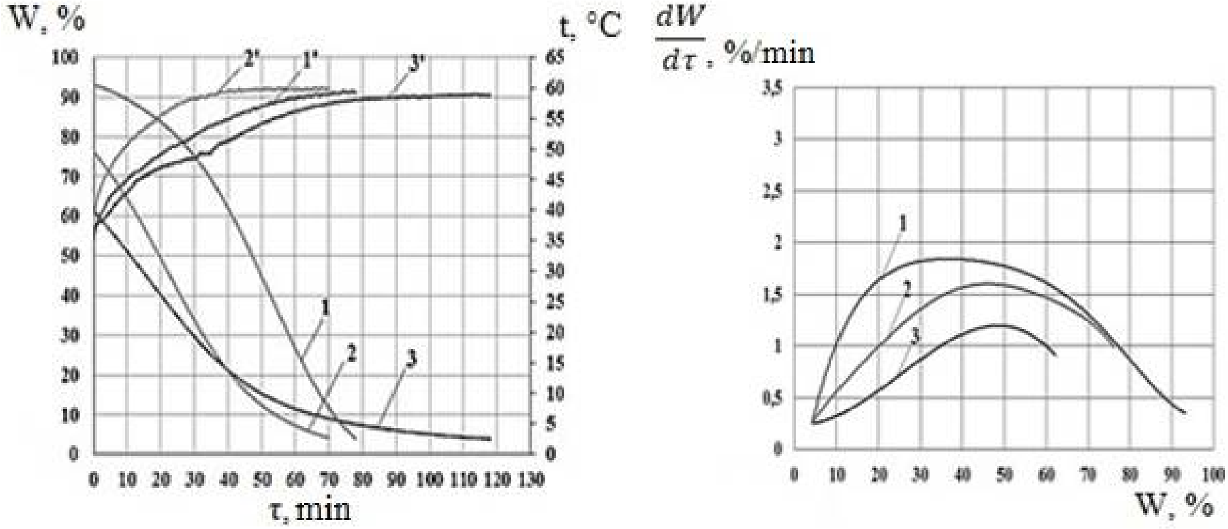
a) *b*)

1 – red beetroot-tomato (3:1); 2 – tomato; 3 – red beetroot.

Fig. 2 – Kinetics (a) and velocity (b) of drying red beetroot, tomato, and their mixture (mode parameters: t = 60 °C v = 3.5 m/s, δ = 10 mm, d = 10 g/kg dry air)

The influence of the composition components on the kinetics of the drying process was also studied on phytoestrogen raw materials - soy-vegetable compositions, where the vegetable component was spinach and sweet potato.

On fig. 3, a presents the drying kinetics (curves *1-3*) and temperature curves (curves 1’-3’) soy, spinach and their mixtures (ratio of components 1:1) [9].



a) *b*)

1, 1' – spinach; 2, 2' - soy-spinach mixture; 3, 3' – soy.

Fig. 3 – Kinetics (a, 1-3), temperature curves (a, 1'-3') and velocity (b) of drying soybean, spinach and their mixture (mode parameters: t = 60 °C v = 2.5 m/s, δ = 15 mm, d = 10 g/kg dry air)

Data on the change in temperature inside the layer of the soybean-spinach mixture depending on the duration of the process (fig. 3, a, curves 1', 2', 3') confirm the reduction in the time to reach the set temperature regime of 60 °C (40 min), which in 2x faster than soy.

The drying velocity curves (fig. 3, b) a characteristic form of colloidal capillary-porous materials and show that the main drying process, the removal of free and bound moisture, occurs in period II, during the period of decreasing speed.

Data on the change in the drying rate depending on the moisture content of the material indicate that the mixture of soybean-spinach components (fig. 3, b curve 2) has a maximum drying rate (N_{max}) – 1.6%/min, 1.34 times higher

N_{max} hydrothermic pre-treated soybeans – 1,19 %/min (fig. 3, *b* curve 3). By adding spinach, which has a maximum drying rate of 1.8%/min.

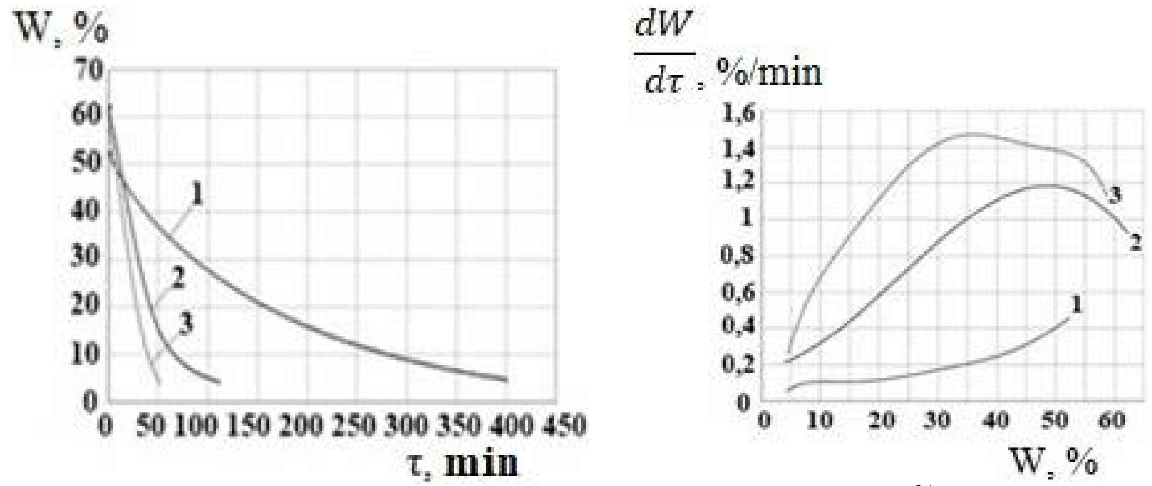
Due to the creation of a soy-spinach mixture, the drying process of spinach is intensified by 10 % and soybeans by 41 %.

The study of the influence of components on the kinetics of the drying process was also carried out on samples of a soybean-sweet potato mixture, with a vegetable component - Vietnamese sweet potato, which was grown on the soils of the Socialist Republic of Vietnam.

Drying curve shapes, fig. 4 also have the characteristic appearance of colloidal capillary-porous materials. The use of a high-temperature drying mode above 65-70 ºC leads to the destruction of carotene, which is contained in sweet potato, therefore it is advisable to use the drying mode at a coolant temperature of 60 ºC (fig. 4).

Vietnamese sweet potato (W_{st} = 52 %) – hard-drying drying object. It takes 6 hours 40 min to dry it to a final moisture content of 4-6%. On fig. 4, a it can be seen that with the combination of soybeans (W_{st} = 62 %) with sweet potatoes in a mixture with a ratio of components 1: 1 (W_{st} = 58 %), there is a significant reduction in the duration of drying, relative to sweet potato, - 8 times and the total drying time is 50 minutes.

Curves of changes in the drying rate depending on the moisture content W of the material (fig. 4, b) confirm the feasibility of developing a soybean-sweet potato mixture (fig. 4, b, cr. 3). It is characterized by higher drying velocity, the maximum drying velocity N_{max} = 1,45 %/min, in comparison with the drying rate of soybean (fig. 4, b, curve 2) and sweet potato (fig. 4, b, curve 1).



b)

a)

1 – sweet potato; 2 – soy; 3 – soy-sweet potato mixture.

Fig.4 – Kinetics (a) and velocity (b) of drying soybean, sweet potato and their mixture.
(mode parameters: t = 60°C, v = 2.5 m/s; d = 10 g/kg d.m., δ = 15 mm)

One of the characteristics of the kinetics of the drying process is the Rebinder number (*Rb*), which determines the ratio of the amount of heat spent on heating the material and on the evaporation of moisture in an infinitely small period of time [9]:

$$Rb = b\frac{\bar{c}}{r} = \frac{\bar{c}}{r}\left(\frac{d\bar{t}}{d\overline{\overline{W}}}\right) \qquad (1)$$

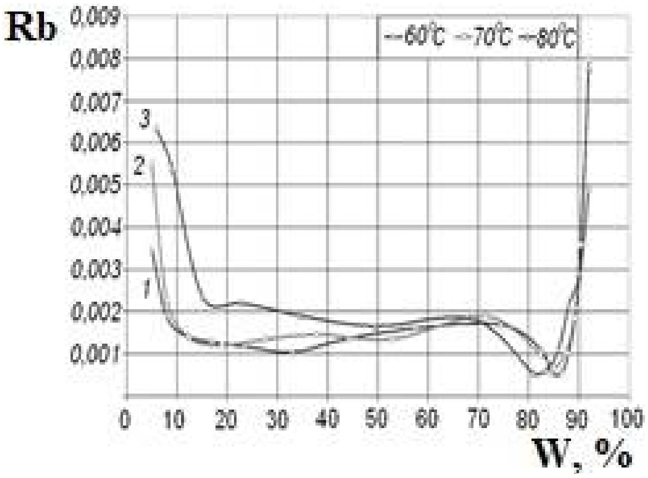
Based on the studies: antioxidant (red beetroot-tomato) and phytoestrogenic (soy-spinach) mixtures, the dependence of the change in the Rebinder number on moisture content (in %) of the material was calculated and graphically depicted.

Fig. 5, a shows that the number *Rb* depends on the temperature of the heat carrier and the moisture content of the material on the example of a red beetroot-tomato mixture. At the beginning of the drying process, the material warms up with a decrease in its moisture content, while the *Rb* number decreases. In the humidity range of 85 - 20%, the value of the *Rb* number is minimal. At this moment, in the vast majority the heat is spent on removing moisture from the material. From a material moisture content of 15%, the *Rb* number increases sharply, so, the most of the heat is spent on heating the material. The nature of the change in the *Rb* number proves the effectiveness of the introduction of phased drying modes [5].

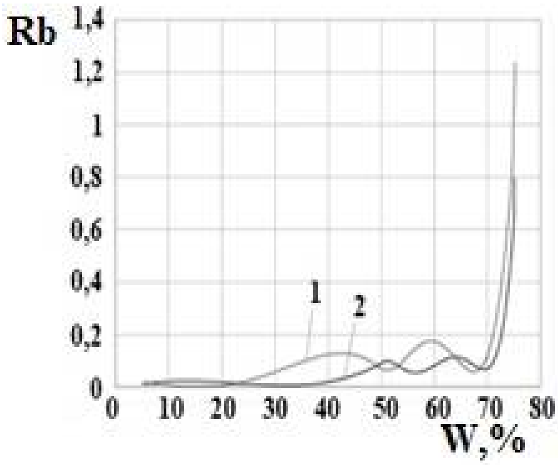
On fig. 5, b shows that at both 60 ºC and 100 ºC heat carrier temperatures Rb has two maxima and two minima in the humidity range of 70-30 %, but the difference between Rb_{max} and Rb_{min} much more for 100 ºC, which confirms the "softness" of the temperature effect of the coolant on the thermolabile material at 60 ºC [12].

Based on the data obtained, phased drying modes were developed for red beetroot-tomato (Fig. 6, a) and soy-spinach (fig. 6, b) mixtures.

Developed step-by-step dehydration modes t = 100/60 ºC, v= 3.5 m/sec, δ = 10 mm (red beetroot-tomato mixture) and t = 100/60 ºC, v= 2.5 m/sec, δ = 15 mm (soy-spinach mixture) intensify the process, reduce the drying time of the red beetroot-tomato mixture by 50% and the soy-spinach mixture by 21%. The use of which made it possible to preserve the nutrients, color and taste of the original components.



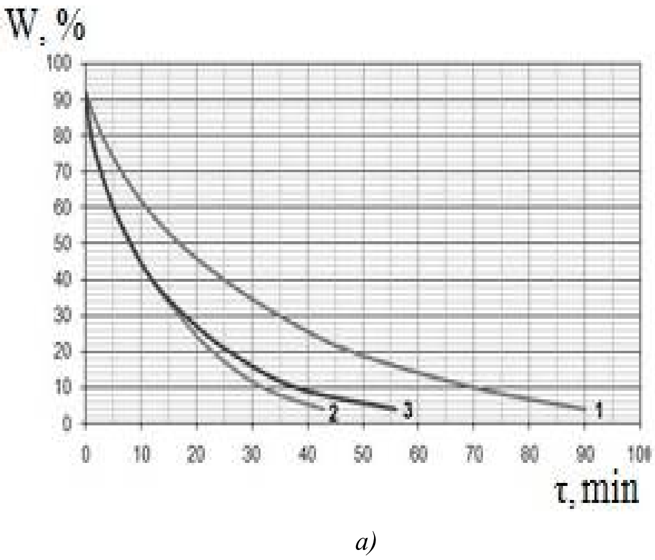
a)



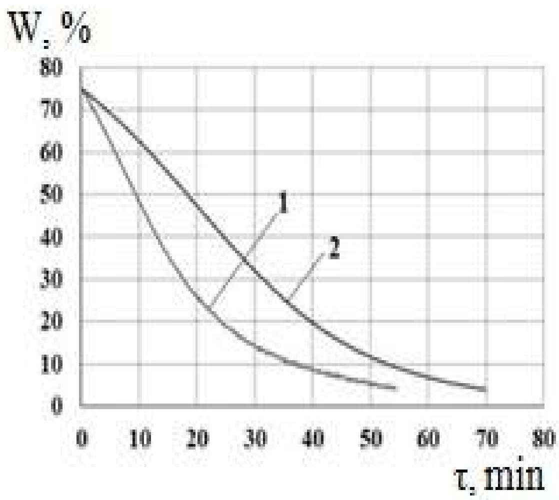
b)

a) red beetroot-tomato mixture. 1 – 60 ºC, 2 – 70 ºC, 3 – 80 ºC;
б) soy-spinach mixture. 1 –100 ºC, 2 –60 ºC.

Fig. 5 – Dependence of the Rebinder number on the humidity of the combined functional material and the temperature regime of the heat carrier



a)

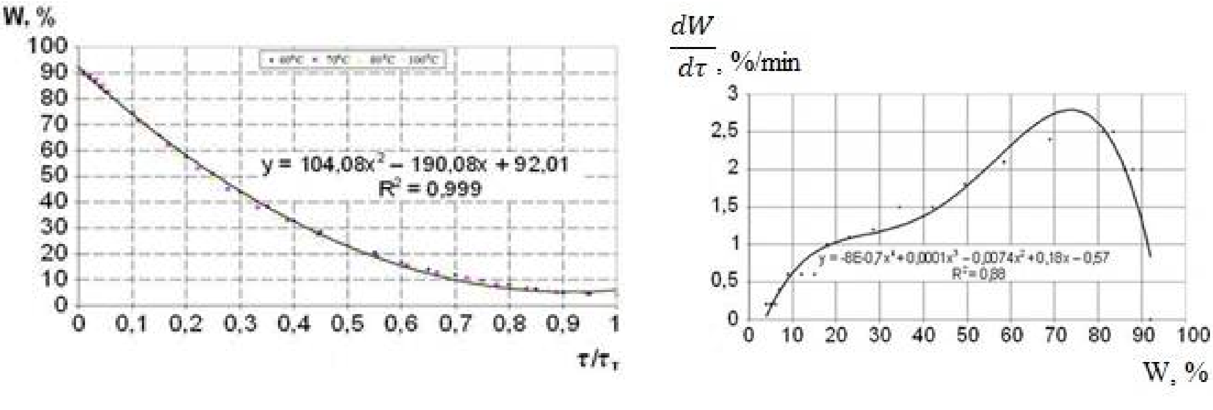


b)

a) red beetroot-tomato mixture (v = 3.5 m/sec, δ = 10 mm, d = 10 g/kg dry air):1 – 60 °C; 2 – 100 °C; 3 – 100/60 °C,
b) soy-spinach mixture (v = 2.5 m/sec; δ = 15 mm, d = 10 g/kg dry air):1 – 100/60 ºC, 2 – 60 ºC.

Fig. 6 – Kinetics of drying combined functional materials depending on the temperature of the heat carrier

Theoretical processing of the obtained experimental data of the antioxidant composition was carried out using the method of V.A. Danilov [14]. On fig. 7, a shows the drying curve of the red beetroot-tomato mixture, which is transferred to the coordinate system W – (τ/τ_T) and transformed into a single generalized drying curve.



a) *b)*

Fig. 7 – Generalized drying kinetics curve in coordinates W – (τ/$\tau_т$) (a) and a generalized drying velocity curve (b) of the red beetroot-tomato mixture

Generalized curves of the kinetics of drying the red beetroot-tomato mixture by the Danilov V.A. coincide with different drying regimes (fig. 7, b). A generalized drying curve can be built from one research curve for drying a red beetroot-tomato mixture obtained in any drying mode, which greatly simplifies the study of drying kinetics.

By graphical differentiation of the generalized drying kinetics curve, as shown in fig. 7, a, we obtained a generalized drying velocity curve for the red beetroot-tomato mixture, which is represented by a smooth curved line (fig. 7, b).

The duration of the drying process of the phytoestrogenic mixture based on soy and spinach on an experimental convective stand was calculated according to the method of Krasnikov V.V. [15]. Generalized drying curves in coordinates *W – (N τ)* are shown in Figure 8. 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.

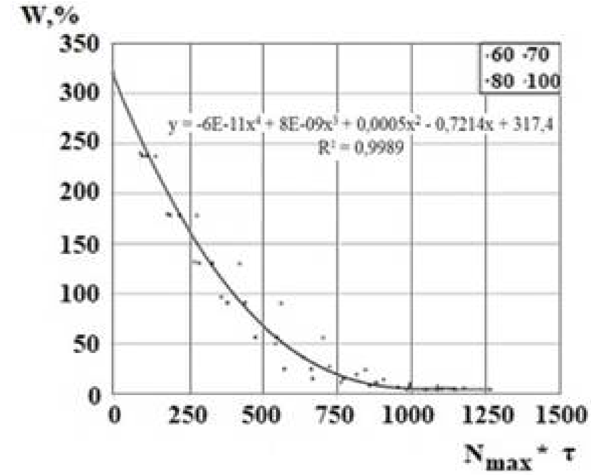


Fig. 8 – Generalized curve of the kinetics of drying the soybean-spinach mixture depending on the influence of the heat carrier temperature: 60 °C; 70 °C;80 °C; 100 °C

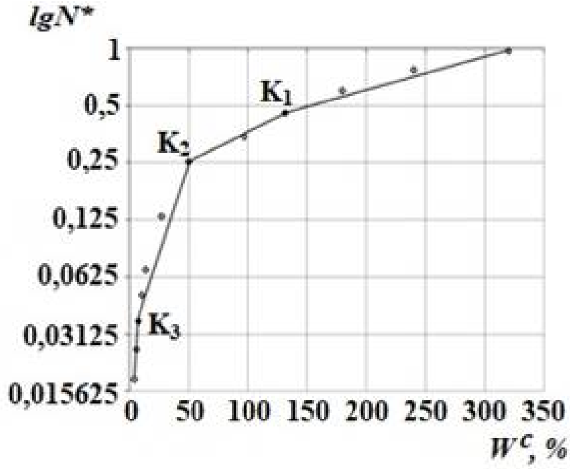


Fig. 9 – Generalized curve of the drying rate of the soybean-spinach mixture depending on the influence of the heat carrier temperature: 60 °C; 70 °C; 80 °C; 100 °C

After graphical differentiation of the generalized drying kinetics curve shown in fig. 8, a generalized drying velocity curve was obtained, which is determined through the equation $N^* = \left|\frac{dW}{d\tau}\right| \div \mathrm{N} = \frac{dW}{Nd\tau} = tg(W, N\tau) = f(W)$.

Value *N** does not depend on the drying mode and is a function of humidity.

Fig. 9 shows that the generalized drying velocity curve is shown in semi-logarithmic coordinates, in the form of a broken line, which consists of four straight lines. What indicates the difference in the kinetics and dynamics of drying in different periods of the process.

The generalized curve of the drying kinetics of the soybean-spinach mixture made it possible to determine the relative drying coefficients. And it became possible to calculate the total duration of drying the soy-spinach mixture.

The total drying time is determined through the equation $\tau = \dfrac{1320}{N}$. The deviation of the values of the calculated from the experimental duration of drying of the soybean-spinach mixture does not exceed 5 %.

Studies of the qualitative characteristics of combined functional materials additionally confirmed the feasibility of using a phased drying regime t=100/60 °C, v = 3,5 m/sec, δ = 10 mm, d = 10 g/kg dry air for red beetroot-tomato and t=100/60 °C, v = 2,5 m/sec, δ = 15 mm, d = 10 g/kg dry air for soy-spinach mixtures. The results of studies [5, 12] showed that the maximum value of betanin retention in a mixture based on red beetroot 96-97% corresponds to the temperature regime of drying 100/60 °C. For a mixture based on soybean, an important indicator is the acid number, which characterizes the degree of lipid oxidation in the biochemical composition of soybeans during drying and further storage. Drying temperature 100/60 °C for soy-based mixtures, it helps to avoid critical values of the acid number.

Lykov A.V. in [16] pointed out that drying is not only a heat engineering, but also a technological process that affects the biochemical properties of the studied materials. Thus, we have achieved not only the intensification of the drying process, but also the preservation of high quality biochemical characteristics of the dehydrated material.

Conclusions. Preliminary preparation of combined functional materials (antioxidant and phytoestrogenic) further reduced the overall duration of the process.

Studies of the kinetics of convective drying of antioxidant raw materials confirmed that it is possible to reduce the duration of the process: 1) by 1.4 times - by changing the shape of a red beetroot sample from plates to chips; 2) an increase in the temperature of the coolant from 60 °C to 100 °C will speed up the drying process by 1.8 times, but this will destroy the red beetroot betanin and it will lose its functional properties; 3) blending red beetroot with tomato in a ratio of 3:1 will allow reaching the final moisture value 1.5 times faster compared to red beetroot and will keep betanin at the maximum level - 96.5%.

It is also possible to intensify the process of convective drying of phytoestrogenic raw materials through the combination of pre-hydrothermally treated soybeans with spinach / sweet potato. Due to the creation of a phytoestrogenic soy-spinach mixture with a ratio of components 1:1, a reduction in the total duration of the spinach dehydration process by 10% and soybean by 41% was achieved, which can also affect the reduction of energy costs.

It was found that when soybeans are combined with Vietnamese sweet potato in a mixture with a ratio of components 1: 1, the drying time is reduced, relative to sweet potato, - 8 times.

Based on the data obtained on the nature of the change in the Rebinder number depending on humidity, the combined functional material and the temperature of the coolant, phased drying modes for functional materials were developed.

The developed step-by-step dehydration regimes intensify the process, reducing the drying time of the antioxidant red beetroot-tomato mixture by 50% and the phytoestrogenic soy-spinach mixture by 21%. The use of which made it possible to preserve the nutrients, color and taste of the original components.

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ДОСЛІДЖЕННЯ КІНЕТИКИ ПРОЦЕСУ СУШІННЯ КОМБІНОВАНИХ РОСЛИННИХ МАТЕРІАЛІВ

Петрова Ж.О., д.т.н., гол. наук. співр., Слободянюк К.С., к.т.н., ст. наук. співр., Самойленко К.М., к.т.н., ст. наук. співр., Вишнєвський В.М., аспірант, Граков О.П., аспірант
Інститут технічної теплофізики НАН України, Київ

Анотація. *Загальна тенденція енергоспоживання, що призводить до збільшення кількості спожитої енергії у світі, показала, що її вартість постійно підвищується, дефіцит енергоносіїв зростає. Отже, на сьогодні актуальною є проблема створення та широкомасштабного впровадження сучасних енергоефективних теплотехнологій, що забезпечують скорочення витрат енергоносіїв та максимальне збереження високої якості зневодненого продукту.*

З метою вирішення вищезазначеної проблеми, у даній роботі розроблено інноваційну підготовку комбінованих рослинних матеріалів. Представлено результати дослідження pH для різних співвідношень столового буряку з ревенем/томатом. Нам вдалося отримати найбільш оптимальне співвідношення компонентів у суміші столовий буряк:ревінь як 2:1, при цьому значення pH становить 3,75, а бетанін в досліджуваному матеріалі після сушіння зберігається на рівні 96,5% для буряк:томат – 3:1, у якому pH становить 3,9, а бетанін – 94,7 %. А також, з метою збереження та підвищення функціональності фітоестрогенних властивостей рослинної сировини, розроблено умови стабілізації рослинних інгредієнтів. Створено суміші з рослинних матеріалів при різному співвідношенні вихідних компонентів рослинного походження та розроблено оптимальні режими сушіння.

Експериментально досліджено кінетику процесу сушіння комбінованих рослинних матеріалів із попередньою їхньою підготовкою.

На основі отриманих даних про характер зміни числа Ребіндера в залежності від вологості, комбінованого рослинного матеріалу та температури теплоносія, були розроблені поетапні режими сушіння.

Теоретичну обробку отриманих експериментальних даних на суміші буряк:томат було виконано за методом В.А. Данилова. Узагальнені криві кінетики сушіння суміші буряк:томат співпадають з різними режимами сушіння.

Тривалість процесу сушіння суміші соя:шпинат на експериментальному конвективному стенді розраховувалася за методом Краснікова В.В. Узагальнена крива кінетики сушіння суміші соя:шпинат дозволила визначити відносні коефіцієнти сушіння. І стало можливим розрахувати загальну тривалість сушіння суміші соя:шпинат. Відхилення значень розрахункової від експериментальної тривалість сушіння не перевищує 5 %.

Ключові слова: тепломасообмін, кінетика сушіння, швидкість сушіння, Ребіндер, комбіновані функціональні матеріали.

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