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Kinetic Bases Of Obtaining Concentrated Forms Of Food Systems Based On Soy-Root-Crop Compositions.

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ABSTRACT

Methodological approaches are presented that allowed to theoretically obtain kinetic models of technological and physicochemical transformation of the composition and properties of soybean and root crops containing physiologically functional ingredients. An innovative method of obtaining protein-vitamin products, developed on the basis of accepted approaches and kinetic models of transformation of raw materials, is proposed.
Keywords: deficiency, protein, kinetics, model, soybean seeds, roots, an innovative way.

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INTRODUCTION

The lack of proteins, vitamins, minerals and is currently one of the most important problems of mankind.

At the same time, the existing food resources, in the form of soybean and root-raw materials, are not used efficiently.

This is due, primarily, to the lack of a scientific base for the development of technologies for processing these types of raw materials into functional food systems.

The aim of the research is to obtain scientifically based data characterizing the kinetic bases of transformation of the composition and properties of soyootroot compositions in the process of their processing into food systems of a functional orientation.

Research tasks

- on the basis of theoretical analysis, to obtain a kinetic model of the accumulation of mineral substances during soaking, swelling and germination of soybean seeds;
- from the standpoint of a diffusion phenomenon, obtain a kinetic model for the extraction of protein and vitamin substances from soybean and root crops;
- based on the analysis of physico-chemical phenomena to justify the kinetic model of thermo-acid coagulation of proteins;
- analytically to obtain kinetic models of mechanical and thermal dehydration of protein-vitamin-mineral coagulate (PVMC);
- to obtain a kinetic model characterizing the ability of the concentrated form of PVMC to restore the composition and properties;
- on the basis of the data obtained, develop an innovative method of obtaining protein-vitamin products.

RESULTS AND DISCUSSION

By analyzing the process of obtaining concentrated forms of polycomponent systems using the soy component, it was established that it includes the following operations [1 - 5]:

1) soaking and germination of soybean seeds in a mineralized aquatic environment, in order to accumulate mineral substances with an appropriate swelling of protein substances in them;
2) preparation of the protein disperse system, by grinding soaked seeds or compositions with the implementation of the extraction of protein substances in the aquatic environment by the method of convective diffusion;
3) the concentration of proteins by precipitation by the method of thermo-acid coagulation;
4) separation of the coagulum from the liquid fraction, followed by squeezing moisture, to a predetermined value;
5) molding the resulting coagulum with its freezing, drying, etc.

The process of soaking of soybean seeds in an aqueous mineralized medium was considered as a process of accumulation of mineral substances due to external diffusion, which occurs with simultaneous swelling of proteins in the two-cotyledon soybean seed.

The kinetics of accumulation of mineral substances was presented taking into account the shape and dimensional characteristics of soybean seeds by the following equation:

$$\tau_a = \frac{0{,}0796 G^{MB} \cdot \sqrt{S/\pi}}{D_{ext} \cdot \Delta C \cdot R^2} \ , \tag{1}$$

where G^{MB} – mass of mineral substances accumulated in two-semolina seed;

S – surface area of soybean seed;
D_{ext} – external diffusion coefficient;
$\triangle C$ – the difference in the concentration of minerals in the aquatic environment and the seed (the driving force of the process);
R – radius of soybean seed taken by the ball.

The kinetics of swelling of protein substances of soybean seeds according to [3, 4] is described by the following dependency:

$$\tau_{sw} = D - F \cdot \ln(A - k_{в}), \quad (2)$$

where D, F and A – empirical coefficients characterizing the process of soaking soybean seeds;
R – coefficient of water saturation with protein substances of soybean seeds, which characterizes the process of swelling.

In this relationship, the coefficient $k_{в}$ represents the ratio of the volume of the swollen seed V_{sw} to the volume of dry seed V_{dr}, respectively with the initial and final humidity W_{in} and W_{f}.

Having taken the seed for the ball at the beginning of the process and for the correct ellipsoid at its end, we have

$$k_{в} = \frac{a_{sw} \cdot b_{sw}^2}{R^3}, \quad (3)$$

where a_{sw}, b_{sw} – the corresponding semi-axes of the ellipsoid, for which the shape of the swollen seed is taken.
R –radius of the ball, which adopted the form of dry change soy.
For the parameter of increasing the linear size of the swollen seed along its length:

$$k_{l} = \frac{2a_{sw}}{k} = \frac{4a_{sw}}{\sqrt{S/\pi}} \quad (4)$$

and width:

$$k_{b} = \frac{2b_{sw}}{k} = \frac{4b_{sw}}{\sqrt{S/\pi}}$$

Given the above provisions, the coefficient of water saturation of soybean seeds is essentially a value equal to the product

$$k_{в} = (k_{\ell} \cdot k_{b}^2) \cdot 100\% \quad (5)$$

or

$$k_{в} = \frac{4a_{sw}}{\sqrt{S/\pi}} \cdot \left(\frac{4b_{sw}}{\sqrt{S/\pi}}\right)^2 = \frac{200,96 \cdot a_{sw} \cdot b_{sw}^2}{\sqrt{S/\pi} \cdot S} = \frac{200,96 \cdot a_{sw} \cdot b_{sw}^2}{\sqrt{S^3/\pi}} \quad (6)$$

The intensity of the process of swelling of protein substances of soybean seeds, depends on the initial and acquired sizes (volumes) of soybean seeds in the process of their water saturation

$$v_{w} = 2\left(a_{sw} - R\right)/\tau_{sw} \quad (7)$$

or

$$v_{w} = 4,186\left(a_{sw} b_{sw}^2 - R^3\right)/\tau_{sw} \quad (8)$$

The kinetics of the process of germination of soybean seeds, to the required length of the sprout, was defined as [2]

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$$\tau_{ger} = l_{ger} / \upsilon_{ger} \tag{9}$$

where l_{ger} - sprout length;

υ_{ger} – seed germination rate.

The process of extraction of protein and vitamin substances from the crushed mass of soaked seeds of soybeans and root crops, representing a binary composition, was considered from the point of view of convective diffusion of protein G_p and vitamin G_v substances from the composition of the binary composition G_c.

For the corresponding extraction time τ_e, we have the system of equations

$$\left.\begin{aligned} \frac{dG_p}{d\tau} &= \varphi_1(G_c - G_p - G_v), \\ \frac{dG_v}{d\tau} &= \varphi_2(G_c - G_p - G_v) \end{aligned}\right\}, \tag{10}$$

where φ_1 and φ_2 – proportionality coefficients.

Dividing the second equation by the first we have that $\frac{dG_v}{dG_p} = \frac{\varphi_1}{\varphi_2}$, from where $G_v = \left(\varphi_2 \cdot G_p / \varphi_1\right) + C$.

With $\tau_e = 0$, $G_p = 0$, $G_v = 0$ and C= 0 and therefore

$$G_v = \varphi_2 \cdot G_p / \varphi_1 \ , \tag{11}$$

Substituting this value G_v in the first equation of system (10) we have that

$$\frac{dG_p}{d\tau} + \left(\varphi_1 + \varphi_2\right) \cdot G_p \tag{12}$$

The general solution of this equation gives

$$G_p = \frac{\varphi_1 \cdot G_c}{\varphi_1 + \varphi_2} + C_1 \cdot \mathrm{e}^{-(\varphi_1 + \varphi_2)\tau_e} \tag{13}$$

Under initial conditions $G_p = 0$ and $\tau_э = 0$ we have that

$$C_1 = -\varphi_1 \cdot G_p / \left(\varphi_1 + \varphi_2\right) \tag{14}$$

and then

$$G_p = \frac{\varphi_1 \cdot G_c}{\varphi_1 + \varphi_2}\left[1 - \mathrm{e}^{-(\varphi_1 + \varphi_2)\tau_e}\right] \tag{15}$$

Substituting this equation into equation (11) we have that

$$G_v = \frac{\varphi_2 \cdot G_c}{\varphi_1 + \varphi_2}\left[1 - e^{-(\varphi_1+\varphi_2)\tau_e}\right] \quad (16)$$

At the same time, the yield of both proteinaceous substances and vitamins from the crushed mass of the binary composition to the saline water environment depends on the degree of grinding. λ_{gr} and final particle shapes

$$G_p = \frac{78,87 \cdot \Delta C \cdot R_2^2}{\left[\frac{(2,54 \cdot a_{sw} \cdot b_{sw}^2)^{0,33}}{D_{ext} \cdot \lambda_{gr}} + \frac{1}{\beta}\right] \cdot \omega}, \quad (17)$$

β – mass transfer coefficient;
ω – rotational speed of soybean root pulp.

The degree of grinding of soaked soybean seeds, as transformed into two-semolina fragments of the original protein-containing raw material in the form of a parabolic half-wedge and similar to them in the shape of root and tuber crop particles, is determined by the obtained dependence

$$\lambda_{gr} = 0,05\ell_3\left(8R_3^2 + 4R_3r_3 + 3r^2\right)/R_h^2 \;, \quad (18)$$

where ℓ_3 – barrel length soaked soybean seed (final size);
R_3 and r_3 – respectively, the radii of the middle and extreme parts of the "barrel".

The kinetic model of the process of simultaneous grinding of soyo-root-crop particles of the composition and extraction of substances from them, taking into account dependencies (17) and (18), has the following form:

$$\tau_e = \frac{1}{\omega} = G_p\left\{0,05\left(2,54 \cdot a_{sw} \cdot в_{sw}^2\right)^{0,33} \cdot \left[D_{ext} \cdot \left(8R_3^2 + 4R_3r_3\right) \cdot \ell_3\right]^{-1} + \frac{1}{\beta}\right\}\left(78,87 \cdot \Delta C \cdot R_h^2\right)^{-1}, \quad (19)$$

where G_p determined by the formula (15).

At the same time, the protein content - G_p, fat - G_f, carbohydrates - G_c, mineral substances - G^{MB} and vitamins - G_v in the liquid phase (in the amount of $G_{dry\ matter}$) is generally defined as [3, 6, 8]:

$$G_i = \left(G_{Hi} - G_{0i}\right)\alpha_i \cdot \eta_i^o, \quad (20)$$

where G_i – content of the corresponding *i-th* food substance in the soy protein dispersion system (SPDS);
α_i – mass fraction of *i-th* food substance in SPDS; η^o – hydronic module.

At the same time, the process of thermo-acid coagulation of protein substances in SPDS is characterized by the aggregation of protein particles of vegetable G_{veg} origin and their precipitation in an amount determined by the ratio and the final total mass of protein substances. $G_p + G_v + G_f + G_c$.

At the same time, the value $G_p = f(\tau)$ and $G_p = f(t^0)$, characterized by addictions [3, 6, 7]:

$$G_p = A - Be^{-c\tau} \;, \quad (21)$$

where τ – coagulation time;

$$G_p = A - Be^{-ct^0}, \quad (22)$$

where t^0 – coagulation temperature.

By means of corresponding transformations of these expressions, according to [3, 6, 7], it was established that these parameters can be determined from the following dependencies:

$$\tau = F - D\ln(F - G_p) \ , \qquad (23)$$

$$t^0 = F_1 - D_1 \ln(F_1 - G_p) \ , \qquad (24)$$

where F, D, F_1, D_1 – empirical coefficients.

The kinetics of the process of coagulation of protein substances in the SPDS, using an acid-berry complex, was considered as the process of their agglomeration, as a result of which the physical mass of the coagulate particles is incremented and precipitated

$$\frac{dm}{d\tau} = -\frac{dS}{d\tau} \ , \qquad (25)$$

or

$$\frac{dm}{d\tau} + \frac{dS}{d\tau} = \frac{d(m+S)}{d\tau} = 0 \qquad (26)$$

$$m + S = const = m_0 + S_0 = m' + S' = C \qquad (27)$$

where m_0, S_0 – initial values of protein particles at time $\tau = 0$;
m', S' – values that these parameters approach over time;
C – constant.

The rate of weight gain of protein agglomerate is a function of the following type

$$\frac{dm}{d\tau} = \gamma(m;\ S) \qquad (28)$$

Given the above dependencies, we have that

$$\frac{dm}{d\tau} = \gamma(m;\ S - m) = p(m) \ , \qquad (29)$$

where p – specific rate of weight gain of sinter.

Let us assume hypothetically that the specific rate of weight gain is subject to the following dependence

$$\frac{dm}{d\tau} = -H \cdot p \ , \qquad (30)$$

where H – additional parameter characterizing the decrease in the rate of growth.

Integrating this equation gives

$$p = p_0 \cdot e^{-H \cdot \tau} \qquad (31)$$

where p_0 – parameter value at time $\tau = 0$.

The joint solution of equations (29) and (31) gives

$$\frac{dm}{d\tau} = p_0 \cdot m \cdot e^{-H \cdot \tau} \qquad (32)$$

Integrating this equation we get

$$\int_{m_0}^{m} \frac{dm}{m} = p_0 \int_{0}^{\tau} \mathrm{e}^{-H\cdot\tau} \cdot d\tau \tag{33}$$

The transformation (33) gives it the following form

$$\ln\left(m/m_0\right) = \frac{p_0}{H}\left(1 - \mathrm{e}^{-H\cdot\tau}\right) \tag{34}$$

This equality will result in the following form.

$$m = m_0 \cdot \exp\left[p_0 \left(1 - \mathrm{e}^{-H\cdot\tau}\right) / H \right] \tag{35}$$

For small values, we have $\tau \cdot \mathrm{e}^{-H\cdot\tau} \approx 1 - H \cdot \tau$ and then

$$m' \approx m_0 \cdot \mathrm{e}^{p_0 \cdot \tau} \tag{36}$$

Subject to when $\tau \to \infty$ weight – *m* agglomerates approaching its value m' and therefore

$$m' \approx m_0 \cdot \mathrm{e}^{p_0/H} \tag{37}$$

Differentiation of equation (32) gives

$$\frac{1}{p_0} \cdot \frac{d^2 m}{d\tau^2} = \frac{dm}{d\tau} \cdot \mathrm{e}^{-H\cdot\tau} - H \cdot m \cdot \mathrm{e}^{-H\cdot\tau} \tag{38}$$

Equating $\frac{d^2 m}{d\tau^2}$ to zero let's find the moment in time $\tau = \tau'$

$$\tau' = \frac{1}{H} \cdot \ln\left(\frac{p_0}{H}\right) \text{ and } m\left(\tau = \tau'\right) = m'/\mathrm{e}\,, \tag{39}$$

Taking into account equality (37), we obtain

$$\frac{dm}{d\tau} = p_0 \cdot m \left[\frac{\ln\left(m'/m\right)}{\ln\left(m'/m_0\right)} \right] = H \cdot m \cdot \ln\left(m'/m\right), \tag{40}$$

where $\frac{dm}{d\tau} = f\left(t^\circ;\ pH;\ M_c\right)$,

t° - temperature SPDS;
pH – active acidity of the system;
M_c – mass fraction of coagulum.

Intensity of coagulum mass increment in SPDS

$$v_m = m_0 \cdot H \cdot \mathrm{e}^{-H\cdot\tau}$$

Analytical dependence to determine the desired (predicted) final coagulum moisture W_c^{δ}, obtained using the approaches given in the papers [3, 6 – 8].

Nature of change W_c^{δ} has the following form:

$$W_c^{\delta} = W_W^{\delta} \cdot e^{-R(P)} = W_W^{\delta} - W_i \ , \tag{41}$$

where W_W^{δ} – initial humidity of protein-vitamin coagulum, %;

W_i – amount of moisture that must be removed from the protein-vitamin coagulate,%;

P – protein-vitamin coagulant pressure;

R – coefficient of proportionality.

At the same time, the mass of moisture, squeezed from a colored or uncolored protein-vitamin coagulate, in one spin cycle is equal to:

$$W_i = \int_0^H \omega_i\left(h\right) \cdot d_h \ , \tag{42}$$

where $\omega_i\left(h\right)$ – distribution function of the liquid phase along the height *h* of the protein-vitamin coagulate layer;

H – height of the layer of protein-vitamin coagulate.

According to [3, 6 - 8], the nature of the function $\omega_i\left(h\right)$ depends on the uniform distribution of the liquid phase over the layer height, the structural and mechanical properties of the protein-vitamin coagulate and its porosity. At the same time, the yield of the liquid fraction, by the end of the spinning process is reduced, and the density of the coagulum increases. Thus, when pressing the liquid fraction from the protein-vitamin coagulum obtained in our case, its mass in the product decreases.

To determine the law of change in the extraction of the liquid fraction from protein-vitamin coagulate, depending on the time t_1 we also assume that the yield of the liquid fraction is directly proportional to its quantity at each time point τ_1.

During spinning, the content of the liquid fraction in the protein-vitamin coagulate also decreases, therefore, in our case, the differential equation is:

$$\frac{dW_i}{dt_1} = -\psi \cdot W_1; \ W_1 > 0; \ \psi > 0 \, , \tag{43}$$

where ψ – coefficient of proportionality.

Then, the dependence of the change in the yield of the liquid fraction from the protein-vitamin coagulate, in the process of its extraction, also has the following form:

$$W_i = W_W \cdot e^{-\tau t_0} \ . \tag{44}$$

Spin duration τ_{sp} gives the conversion of this equation

$$\tau_c = \frac{2,3}{\psi} \lg\left(W_W / W_i\right) \tag{45}$$

For the final moisture at the time τ_c, its value will also be determined

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$$\tau_c = \psi_0 \lg\left(W_W / W_c\right) \tag{46}$$

where ψ_0 – empirical coefficient equal to $2,3/\psi$.

The intensity of the extraction of serum from protein-vitamin coagulate v_{sp} determined according to the expression [6]

$$v_{sp} = W_H \cdot \psi \cdot \mathrm{e}^{-\psi t_1} \tag{47}$$

The dependence of the pressure P on the time of pressing of the protein-vitamin coagulate τ_p , according to [3, 4, 8] also has the following character

$$P = P_{max} \cdot \left(1 - e^{-c\tau_P}\right), \tag{48}$$

where P_{max} – maximum pressure of protein-vitamin coagulate pressing;
c – empirical coefficient.

The final moisture content of the protein-vitamin coagulum W_c also depends on its initial moisture content W_W and therefore the following equality [3, 4, 8]:

$$W_c = W_W \cdot e^{-R\left[P_{max} \cdot \left(1 - e^{-c\tau P}\right)\right]} . \tag{49}$$

The kinetic model of the drying process characterizes the duration of moisture removal from the protein-vitamin composition, by analogy with [3, 4, 8]:

$$\tau_C = \frac{2,3}{C} \lg\left(W_W / W_k\right). \tag{50}$$

where W_c – final moisture protein-vitamin coagulum;
C – empirical coefficient.

By analogy with the data given in [3, 4, 8], the volumes of granules up to V_{gr}^W and after V_{gr}^C drying express how

$$\left.\begin{aligned} V_{gr}^W &= \frac{\pi \cdot d_{gr}^W}{4} \cdot h_W; \\ V_{gr}^{WC} &= \frac{\pi \cdot d_{gr}^C}{4} \cdot h_C; \end{aligned}\right\}, \tag{51}$$

where d_{gr}^W and d_{gr}^C – the diameter of the granules, respectively wet and dried;
h_W and h_C – length of the granules, respectively wet and dried.

The drying rate characterizing its intensity is equal to

$$v_C = 0,785\left(d_{gr}^W \cdot h_W - d_{gr}^C \cdot h_C\right) / \tau_C , \tag{52}$$

The kinetic model of the drying process, by analogy with [3, 4, 8], takes the form

$$\tau_C = 0,785 \cdot \left(d_{gr}^W \cdot h_W - d_{gr}^C \cdot h_C \right) \Big/ v_C \quad (53)$$

In accordance with [3, 4, 8], the coefficient of shrinkage rate will be

$$k_{sh} = \frac{V_{gr}^W}{V_{gr}^C} = \frac{d_{gr}^C \cdot h_C}{d_{gr}^W \cdot h_W} \quad (54)$$

The dependence characterizing the kinetics of the drying process of a wet granulate also has the form

$$\tau_s = A - B \cdot \ln\left(D - S_d\right) , \quad (55)$$

where *A*, *B*, *D* – empirical coefficients;
S_d – strength of the dried granulated product.

The main indicators of the properties of dried concentrates are their swelling, digestibility and extract content.

It is known that the two second indicators are largely dependent on swelling, and therefore a theoretical analysis has been carried out of the process of swelling of a granulated concentrate with a soy component.

The equation of the kinetics of the process of swelling of granular concentrate has the following form [3, 4, 8]:

$$\tau_W = \ln\left(1 - \frac{M_k^{max}}{M_{ki}}\right) \Big/ R , \quad (56)$$

where τ_W – duration of protein swelling of the dried multicomponent system;
R – coefficient characterizing the ability of previously dried proteins to swell (the so-called memory of proteins).

The resulting kinetic models were implemented in the development of a large series of innovative methods for preparing food functional systems [3] and, including protein-vitamin products based on soy-carrot, soy-pumpkin, soy-beet and other binary compositions [9].

CONCLUSION

Obtained theoretically, scientifically based data characterizing the kinetic features of the preparation of concentrated forms of protein-vitamin-mineral food systems based on soybean-root compositions, allow us to design functional products with significant concentrations of physiologically functional food ingredients.

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