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Physicomechanical and drying properties of soybean seeds under low-temperature convective drying

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ABSTRACT
The peculiarity of the soybean drying process is that it slowly releases moisture, making it easily damaged by mechanical movements. The soybean shell dries faster, with the surface quickly dehydrating, while the central part remains moist. Soybeans must be dried so that the rate of moisture evaporation from the surface of the grain does not exceed the rate of moisture movement from the centre of the grain to its surface. Soybeans contain more protein and fat compared to grains of other crops. The large amount of protein in soybeans creates favourable conditions for the development of mould fungi. Additionally, soybeans are highly hygroscopic. Therefore, it is relevant to conduct a study of the characteristics of soybean seeds. The primary objective is to optimize the low-temperature convective drying process of soybean seeds by analyzing their physicomechanical and thermophysical properties, as well as evaluating the impact of drying temperature on seed germination and quality. In particular, an analysis of physico-mechanical, thermophysical, heat and mass transfer, kinetic, and biochemical characteristics was carried out. In the article, alongside a review of the literature concerning the properties of soybean seeds by various authors, original research has also been conducted. These properties depend on the action of a complex of factors, including the temperature and humidity of the heat carrier, seed humidity, and other variables. Knowledge of these properties enables the drying process to be carried out effectively and to be intensified. The properties presented, based on both the findings of other authors and the author's research, provide an opportunity for a comprehensive assessment of these characteristics. The original research can be divided into three stages, aimed at determining the following properties of soybean seeds as a drying object: physico-mechanical, thermophysical, and heat and mass transfer properties. The heat and mass transfer characteristics are calculated based on physico-mechanical, thermophysical, and experimental studies of drying soybean seeds. Drying of soybean seeds is conducted under low-temperature conditions to preserve the quality characteristics of the material. Increasing the temperature from 40 to 60°C intensifies the drying process 2.125 times. The resulting soybean seeds exhibit a germination rate of 90–96%, which decreases with increasing temperature.

Keywords: properties, soybean, convective drying, intensity, germination

INTRODUCTION
There are currently over 1,000 uses for soybeans worldwide. Currently, soybeans are used to make a variety of highly nutritious products - oil, curd products, fermented milk, kefir, pate, confectionery and other products. Soybeans are also used in the production of sausages, bakery and pasta products, chocolate, sweets, coffee, cocoa, cakes, various sauces, as well as salads and preserves, made from immature seeds and sprouts.

A crucial aspect of soybean cultivation is its post-harvest processing and storage. Timely harvesting of soybean seeds allows the grain to be collected with a moisture content of 18-20%, and in bad weather conditions, the humidity can reach 25-30%. It is not possible to store soybeans at such moisture, as this can lead to self-heating and the development of microflora, which negatively affects its quality and increases losses. Therefore, it is necessary to reduce the humidity to an equilibrium level of 12%, which can only be achieved by drying in specialized installations.

Timely post-harvest processing and pre-sowing preparation are the main conditions for achieving high sowing qualities and seed storage. Therefore, there is a need for comprehensive research into the properties of soybean seeds as an object of drying, which affect effective processing and preservation of natural characteristics.

Various authors have studied the properties of soybean seeds as a drying object, but most publications are devoted to identifying the physico-mechanical properties of seeds. In particular, the dimensions, shape, surface area, porosity, bulk density, and other characteristics have been examined. These characteristics are used to calculate thermophysical properties, as well as heat and mass transfer characteristics.

When determining the heat and mass transfer characteristics, the peculiarity of drying soybean seeds is considered. The complexity of the drying process lies in the fact that the soybean shell dries faster than the kernel, begins to increase and, under the pressure of the kernel, ruptures, resulting in the separation of the cotyledons **[1]**, **[2]**, and **[3]**.

For the best quality of soybean seeds, the heating temperature of the material should not exceed 43°C. However, studies indicate that the temperature can be increased to as high as 60°C, which primarily depends on the drying conditions and the type of drying unit **[4]**, **[5]**, and **[6]**.

To maintain high viability and form healthy, resistant plants, soybean seeds must be stored under optimal conditions. The key factors that most affect the reduction of seed germination are temperature and humidity **[7]**, **[8]**. However, in addition to these parameters, an important aspect is also the constant movement of seeds during the drying process. As noted **[9]**, improper intensification of mechanical movement during drying can lead to microdamage or hidden structural deformations, which negatively affect the physiological quality of the seed material. Therefore, not only the drying temperature of soybean seeds is important, but also its geometric parameters that affect the mechanics of movement during the drying process.

To determine the biochemical characteristics of soybean seeds, in particular, the determination of germination after drying, studies were conducted on drying soybeans from an initial moisture content of 22% to a final moisture content of 12% at a heat carrier temperature of 54.4°C and a relative humidity below 40%, which indicated a decrease in seed germination and cracking with an increase in the number of cracks in the seed coat **[10]**, **[11]**, and **[12]**. That is, overdrying problems can occur not only with increasing heat carrier temperature but also if the relative humidity of the air is below 35 to 40 percent. Severe overdrying can cause reduced germination and increased brittleness of soybean seeds **[13]**, **[14]**, and **[15]**.

Scientific Hypothesis

The properties of soybean seeds, including their physico-mechanical and thermophysical characteristics, significantly influence drying behavior and outcomes. We hypothesize that optimizing the drying temperature will enhance drying efficiency while preserving germination capacity and physical integrity of the seeds.

A properly selected drying regime allows you to reduce the bacterial effect on the seeds while preserving their quality.

Objectives

The primary objective is to optimize the low-temperature convective drying process of soybean seeds by analyzing their physico-mechanical and thermophysical properties, as well as evaluating the impact of drying temperature on seed germination and quality.

Additional objectives: to investigate the physico-mechanical properties of soybeans; to investigate the thermophysical characteristics of soybeans; to establish the heat and mass transfer characteristics during soybean drying in an experimental convective installation; to evaluate the biochemical properties of soybeans after drying; to determine the criterion for optimising the drying process.

MATERIALS AND METHODS

Samples

Samples description: Soybean seeds of the "Kniazhna" variety.

Samples collection: Samples were taken from the total volume into 25 kg bags and temporarily stored at a temperature of 18-20°C.

Samples preparation: The samples were unpacked, 10 g of each sample was taken for testing. The soybean seed samples were selected to reflect the average quality of the total crop. The seed should be clean and intact, with no signs of damage or foreign matter. Grain parameters were tested at four moisture levels (8–22%).

Number of samples analysed: The number of samples ranged from 3 to 9 in each of the conducted physico-mechanical and thermophysical studies, with a total of 15 to 21 samples.

Chemicals

-

Animals, Plants and Biological Materials

For experimental studies, soybean seeds *Glycine max (L.), Merr.* or *Soja hispida Moench* variety "Kniazhna" were used. (Supplier: Institute of Feeding and Rural State of Podillya NAAN, Vinnytsia, Ukraine).

Instruments

Electronic calliper with a scale length of 150 mm and a measurement accuracy of 0.01 mm (Miol, Ukraine). Laboratory scales TBE with a measurement accuracy of 0.001 g (TECNOWAGY, Ukraine). Differential microcalorimeter DMKI-01 (Institute of Engineering Thermophysics of the Ukraine National Academy of Sciences) (Figure 1) **[16]**. Experimental convective drying stand with an automated information reading and processing system (Institute of Engineering Thermophysics of the Ukraine National Academy of Sciences) (Figure 2) **[17]**.

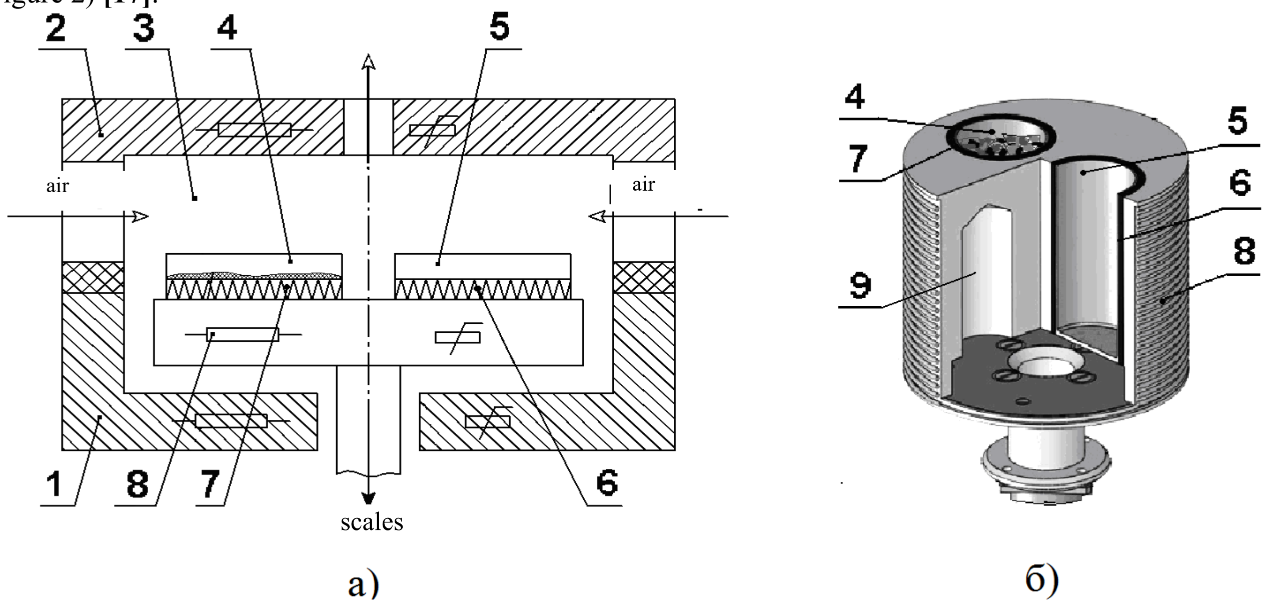


Figure 1 Schematic diagram of the DMKI-01 thermal block.
Note: (a) and the calorimetric platform with cylindrical cells (b): 1, 2 – upper and lower thermostatic blocks; 3 – working chamber; 4 – cell with soybean seed sample; 5 – cell with standard; 6, 7 – heat flux transducers; 8 – calorimetric platform housing with main electric heater; 9 – cavity.

The device consists of a thermal block (Figure 1a), analytical balances, a compressor, an electronic control unit, and a personal computer with the corresponding software. To study soybean seeds, a calorimetric platform with cylindrical cells was used, where the heat flux transducer is placed along the perimeter of the cell walls (Figure 1b).

The experimental drying stand is shown in Figure 2 **[17]**.

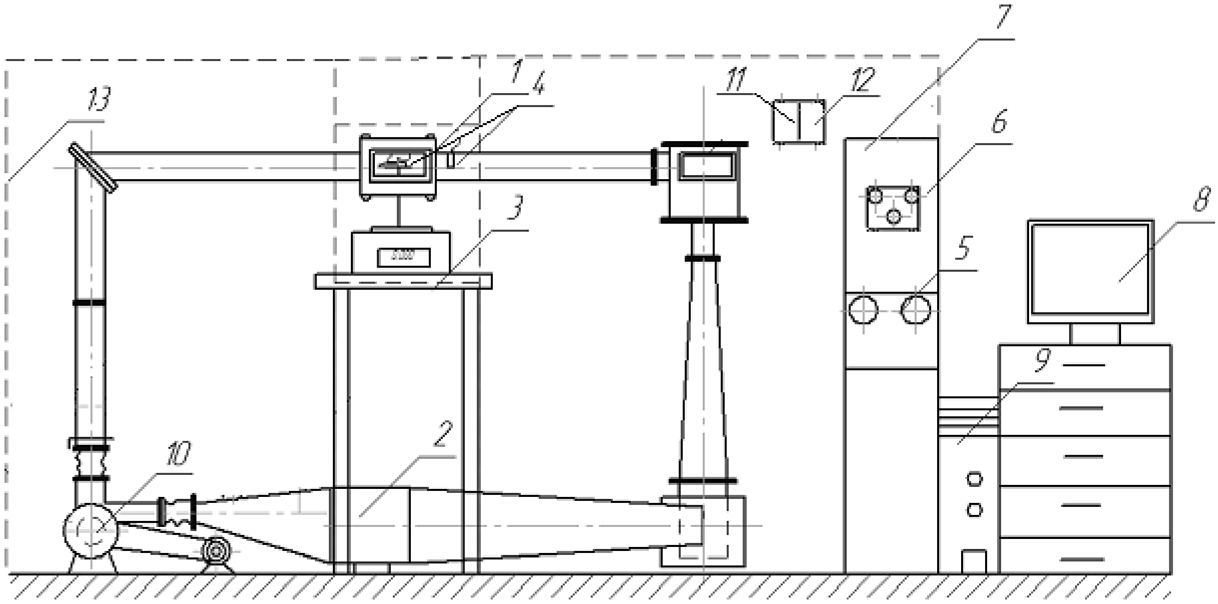


Figure 2 Scheme of a convective drying stand with an automated information reading and processing system. Note: 1 – drying chamber; 2 – electric heaters; 3 – digital scales A D -500; 4 – chromel-copel thermocouples (2 pcs); 5 – temperature regulator in the drying chamber; 6 – heat carrier speed regulator; 7 – control panel; 8 – monitor; 9 – computer; 10 – fan; 11 – analog-digital converter (i-7018); 12 – interface converter (i-7520); 13 – heat-insulating frame.

The experimental stand consists of a system of insulated air ducts, a drying chamber (1) with devices for heating (2) and heat carrier circulation (10), a system for controlling and maintaining temperature (4,5) and heat carrier speed (6), and a system for automatically collecting and processing information about the progress of the material dehydration process (3,8,9,11,12).

The information collection and processing system includes a computer (8,9), digital scales A D-500 (3), and a specially developed automated program, a temperature measurement channel consisting of an analogue-to-digital converter (i-7018) (11) and an interface converter (i-7520) (12). Analogue signals from thermoelectric sensors (4) transmitted from the drying chamber during the research were converted by an analogue-to-digital converter (i-7018) (11) into digital form and transmitted to the computer using an interface converter (i-7520) (12).

Laboratory Methods

1. The determination of the physical and mechanical properties

The determination of the physical and mechanical properties of soybean seeds was obtained by the method of direct measurements and the method of analytical calculation of dependencies.

Physico-mechanical properties of soybean seeds and seed sizes were investigated using callipers. The length (l), width (w), and thickness (t) were determined depending on the moisture content and were measured for 100 seeds by a random sampling method (Figure 3) **[18]**, **[19]**, and **[20]**.

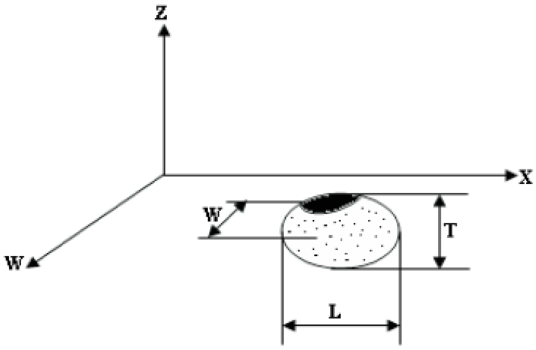


Figure 3 Measurement of soybean dimensions.

The geometric mean diameter, sphericity, and surface area of the grain were determined using the formulas presented in Table 1.

Table 1 Equation for calculating the physico-mechanical characteristics of soybeans.

Characteristics	Equation
Geometric mean diameter, mm	$D_g = (lwt)^{0.333}$, l – length, mm; *w - width, mm; t – thickness, mm*
Sphericity	$\phi = \left[\frac{B(2l - B)}{l^2} \right]^{1/3}$, where: $B = (wt)^{0,5}$
Grain surface area, mm^2	$S = \frac{\pi B l^2}{2l - B}$

The mass of seeds was determined by weighing on laboratory scales.

2. The determination of the heat capacity properties

The determination of the heat capacity properties of soybean seeds was obtained using the standard step-by-step scanning method on a differential microcalorimeter DMKI-01.

To determine the specific heat capacity of soybean seeds, a differential microcalorimeter was used. The determination was carried out according to a standardized method using a step-by-step scanning method at 5°C intervals. Based on the data obtained, the specific heat capacity of seeds was determined at a temperature of the middle of the temperature stage using the formula:

$$c_i = \frac{\int_{\tau_f}^{\tau_i} Q(\tau) d\tau}{m(t_i - t_f)}, \qquad (1)$$

Where: c – specific heat capacity of the material at the temperature of the middle of the temperature step, *kJ /(kg·K)*; m – mass of the material, kg; t_i and t_f – temperature of the beginning and end of the temperature step, °C.

3. The study of heat and mass transfer characteristics

The study of heat and mass transfer characteristics of soybean seeds was conducted using the developed method for determining kinetic characteristics, which employed the automated program "Sooshka," and analytical methods for calculating heat and mass transfer characteristics.

The study of the drying process of soybean seeds to determine the kinetic characteristics was carried out on an experimental drying stand. The determination of the heat and mass transfer characteristics of soybean seeds of the Kniazhna variety was carried out according to the dependencies presented in Table 2.

Table 2 Calculation dependencies for determining heat and mass transfer and kinetic characteristics of soybean seed drying.

Parameter	Calculated dependencies
Final heating temperature of soybeans *θ, °C*	Determined from Figure 5
Drying duration *τ, min*	Determined from Figure 5
Drying rate *dW/dτ, %/min*	Determined from Figure 5
Heating rate *dθ/dτ, %/min*	Determined from Figure 5
Heat capacity of soybeans *c, KJ/kg °C*	Determined from Figure 4 $-0.0376t^2 + 9.49t + 1613.8$
Heat flow *q, W/m^2*	$rg\frac{dW}{d\tau} + cg\frac{d\theta}{d\tau}$
Heat transfer coefficient *α, W/m^2°C*	$\frac{1000q}{(t-\theta)}$
Nusselt criterion *Nu*	$\alpha\frac{l}{\lambda_n}$

Reynolds criterion *Re*	$\alpha \frac{V}{v_n}$
Marking	*r* – specific heat consumption for moisture evaporation, *kJ/kg;* *g* – ratio of absolutely dry mass to surface area, kg/m^2*;* *l* – length of soybean seeds, *m* (*l = 0.0067 m) (as determined from author's own research, presented in Table 3);* λ_a – thermal conductivity of air, *W/(m K);* *V* – heat carrier speed, *m/s* (*V =1.5 m/s);* v_a – kinematic viscosity of air, m^2/s.

Description of the Experiment

Study flow: At the first stage of the experiment, soybean samples from different batches were selected. The initial moisture content of soybean seeds was determined. The physical and mechanical properties of soybean seeds, such as size and shape, surface condition, bulk density, surface area, porosity, were determined. At the second stage, the thermophysical characteristics of soybean seeds were determined: specific heat capacity, thermal conductivity coefficient, and thermal diffusivity coefficient. At the third stage, the soybean seed drying process was investigated to determine heat and mass transfer and kinetic characteristics. At the final stage, the results were processed, subjected to statistical analysis, and the validity of our hypotheses was verified.

Quality Assurance

Number of repeated analyses: 3 repeated analyses.

Number of experiment replication: 3 experiment replications.

Reference materials: None.

Calibration: Each instrument was calibrated before each experiment, and calibration checks were performed regularly to maintain measurement accuracy.

Laboratory accreditation: The experiments were conducted in an accredited laboratory of the Institute of Engineering Thermophysics of the Ukraine National Academy of Sciences.

Data Access

Data supporting the results of this study are not publicly available.

Statistical Analysis

Statistical analysis was performed using Excel and Mathcad 15 software.

To analyze the obtained experimental data on soybean seed drying, a set of statistical processing methods was employed, which enabled the investigation of the influence of various factors on soybean quality **[20]**, **[21]**, and **[22]**. The primary statistical analysis was conducted using multivariate regression analysis. For the statistical assessment of soybean seed germination, a study was conducted to examine the three-factor effect: coolant temperature, coolant velocity, and initial seed moisture. The germination of the material was determined under the influence of various factors. The results of the three-factor experiment are given according to the second-order orthogonal compositional plan.

The regression model enabled the identification of the main factors that significantly affect both drying duration and soybean quality. The significance of the factors was determined using the F-criterion and p-values, with a significance level of $p \leq 0.05$. The results of the analysis of variance confirmed the significance of the selected factors.

RESULTS AND DISCUSSION

Soybean seeds as an object of drying are characterised by the following properties: physico-mechanical, thermophysical, and heat-mass transfer. These properties depend on the action of a complex of factors, such as temperature and humidity of the heat carrier, seed humidity, and others. Knowledge of these properties enables an effective drying process, allowing for the determination of rational drying modes **[21]**, **[22]**, and **[23]**.

The initial material is typically a mixture of soybean seeds and weeds, along with mineral and organic impurities. The task is to isolate the most valuable seeds (i.e., from which the most vigorous plants are obtained) without changing the components of the starting material. For this purpose, the characteristics of mixture separation are utilized, selected based on the nature of the mixture, its peculiarities, and the physico-mechanical properties of the culture and varieties.

When selecting the most valuable seeds, the relationship between the biochemical properties of the seeds, which determine the yield and value of a given crop, is taken into consideration. and their physico-mechanical parameters.

The physico-mechanical properties of seeds include size and shape, surface condition, bulk density, porosity, and flowability of the grain mass, etc.

The presented results of research on the physico-mechanical properties of soybeans from changes in material moisture content in the range of 0-16% are summarised in Table 3.

Research by various authors **[22]**, **[24]**, **[25]** as well as the author's own investigations, indicates differences in the results concerning the physico-mechanical properties of soybeans, which are attributed to varietal characteristics of the seeds, with deviations between the indicators not exceeding 11%.

Determination of thermophysical characteristics of soybean seeds – characterised by the following parameters: specific heat capacity *c,* thermal conductivity coefficient λ*,* and thermal diffusivity coefficient *a,* which change in the process of heat and mass transfer. The reserves of intensification of the drying process depend on their values.

The heat capacity *c* characterises the property of a material to accumulate heat as its temperature increases. Since the heat capacity depends on temperature, each of its values must be related to the temperature or its average value to a specific temperature interval.

The thermal conductivity coefficient λ characterises the thermal conductivity properties of the grain. It depends on pressure, temperature, humidity, porosity, bulk density, and additional heat transfer due to convection and radiative exchange in the pores.

The thermal diffusivity coefficient *a* characterises the rate of temperature equalisation at different points of the body's temperature field during heating and cooling

Table 3 Physico-mechanical properties of soybeans (deviations in brackets).

Property	**Soybean Kniazhna variety**	
Humidity, %	0	6.4
Length, mm	6.29 ±0.21	6.67 ±0.55
Width, mm	5.0 ±0.1	5.67 ±0.63
Thickness, mm	4.68 ±0.38	4.9 ±0.4
Average diameter (arithmetic / geometric), mm	5.32 / 5.28	5.75 / 5.70
Weight of 1000 pieces, g	121.5	126.5
Sphericity	0.877	0.901
Grain surface area, mm^2	38.12	39.41
Porosity, %	38.5	40
Bulk density, kg/m ^{3}	680	650

Thermophysical properties of soybeans have been little studied in the literature; therefore, we conducted additional studies to determine the heat capacity as a function of temperature and moisture content of the seeds. The results of the experiments are summarised in a table, and the corresponding dependencies are constructed (Table 4).

Table 4 Thermophysical characteristics of soybean seeds.

Property	**Soybean Kniazhna variety**		
Humidity, %		8	
Temperature, °C	40	60	80
Specific heat capacity *s*, J/(kg·K)	1933	2048	2132

From the presented research data, and the results of other authors **[21]**, **[23]**, **[26]**, the thermophysical characteristics of soybean seeds depend on the temperature of the heat carrier and the moisture content of the material, as well as on varietal characteristics.

The original research results presented on determining the heat capacity of soybean seeds were obtained in the temperature range of 32.5 to 92.5°C (Figure 4).

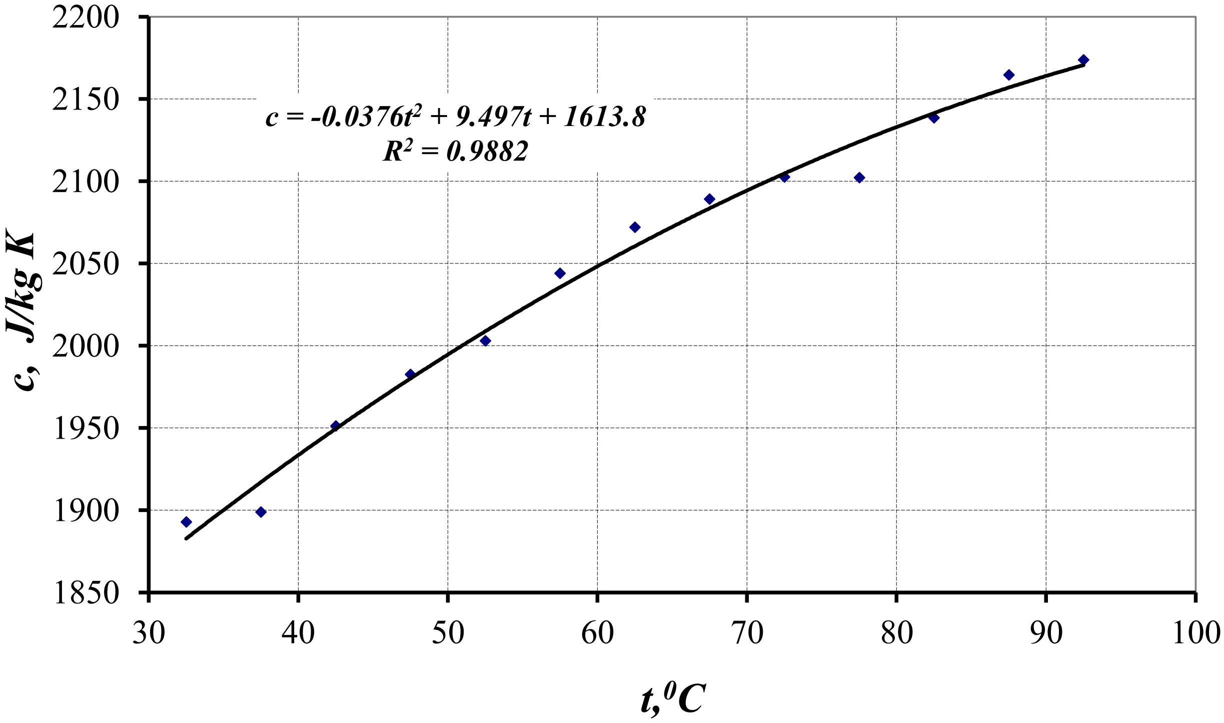


Figure 4 Heat capacity of soybean seeds of the “Kniazhna” variety with an initial moisture content of 8%.

The heat capacity of soybean seeds with an initial moisture content of 8% increases from 32.5 to 92.5°C, resulting in values of 1893 and 2137 kJ/kg.

To determine the heat capacity of soybean seeds, Equation (2) can be proposed, which more accurately describes the process using the following expression:

$$c = -0.0376t^2 + 9.49t + 1613.8 \qquad (2)$$

For the seed grain's growth, the embryo plays an important role, as its tissues consist of living cells. Nutrients for the embryo come from the endosperm. In this regard, when drying the grain, the direction of the moisture flow plays an important role; if the liquid flow is directed from the inside, then water-soluble nutrients are transferred from the endosperm to the embryo. It is therefore necessary to establish drying conditions in which the thermal flow of moisture in the liquid state is directed from the inside to the surface, and the evaporation zone is located as close as possible to the outer surface of the seed.

To characterise the heat and mass transfer properties of soybean seeds as a drying object, the drying process will be examined using an experimental drying stand. To preserve the seed properties of soybean material, it is necessary to dry it at low-temperature regimes (Figure 5).

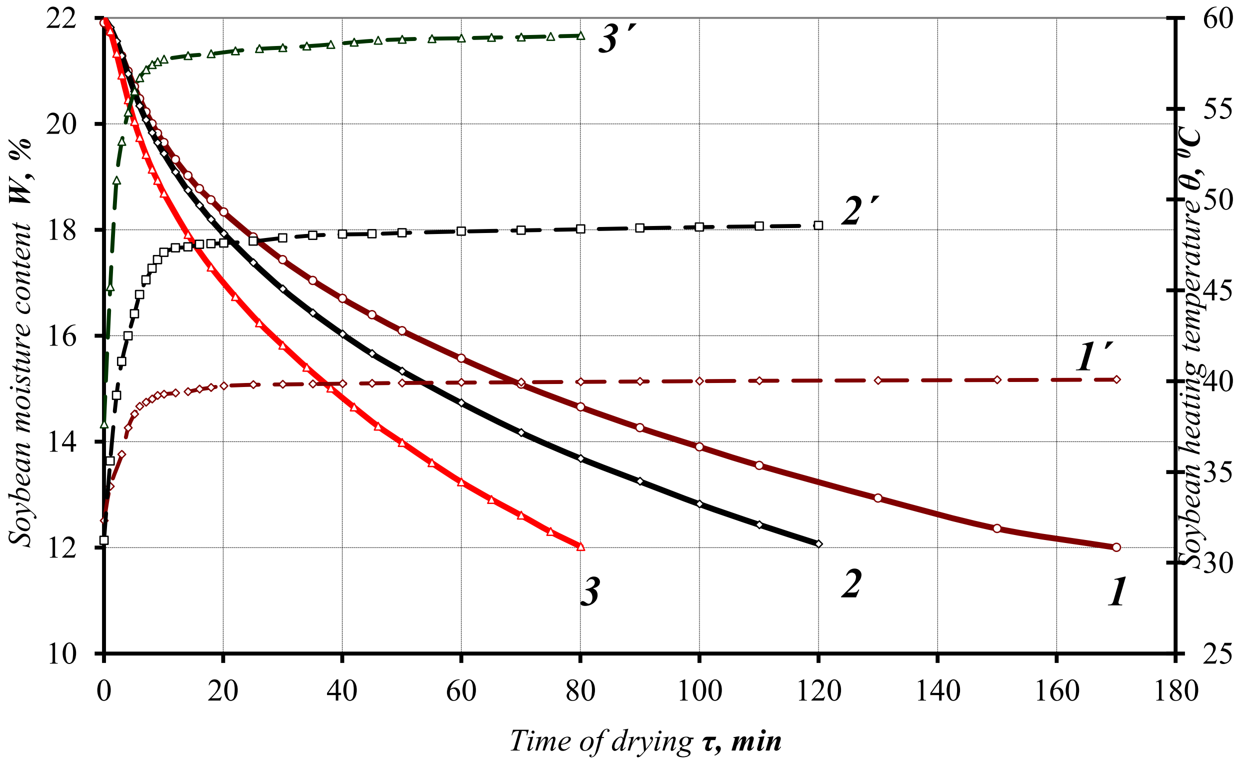


Figure 5 Study of soybean seeds as a drying object with the following parameters: heat carrier speed *V = 1.5 m/s,* moisture content at the entrance to the drying chamber *d = 10 g/kg dry matter* and the temperature of the heat carrier: *1.1´ – 40°C, 2.2´ – 50°C, 3.3´ – 60°C.*

The determination of heat and mass transfer, as well as the kinetic characteristics of soybean seed drying, is presented in Figure 5, and the calculations are summarized in Table 5.

Table 5 Heat and mass transfer and kinetic characteristics of drying soybean seeds of the Kniazhna variety.

Parameter	**Max. parameter values at heat carrier temperature *t, ° C***		
	40	**50**	**60**
Final heating temperature of soybeans *θ, °C*	39.5	48.5	58
Drying duration *τ, min*	170	120	80
Drying rate *dW/dτ, %/min*	0.28	0.32	0.46
Heating rate *dθ/dτ, %/min*	1.79	4.17	7.2
Heat capacity of soybeans *c, KJ/kg °C*	1.93	1.99	2.05
Heat flow *q, W/m²*	0.22	0.29	0.47
Heat transfer coefficient *α, W/m²°C*	25.45	34.92	45.75
Nusselt criterion *Nu*	6.45	8.63	11.04
Reynolds criterion *Re*	619	585	554

With increasing heat carrier temperature, the maximum drying rate increases, so at a temperature of 40°C the drying rate is 0.28%/min, increasing the temperature to 60°C increases the drying rate to 0.46%/min.

When analysing the germination of soybean seeds of the "Kniazhna" variety, it is possible to note high germination at a heat carrier temperature of 40°C, in which germination is 96%, an increase in heat carrier temperature by 10°C (in the temperature range from 40 to 60°C) reduces soybean seed germination by 3%. However, based on the intensity of drying and germination of soybean seeds in the specified temperature range, it is most advisable to choose a temperature of 50°C with germination of 93% **[27]**.

Figure 6 shows a comparison of the initial germination before drying and the germination in the recommended intensive drying mode of 50°C, which differs by 6%.

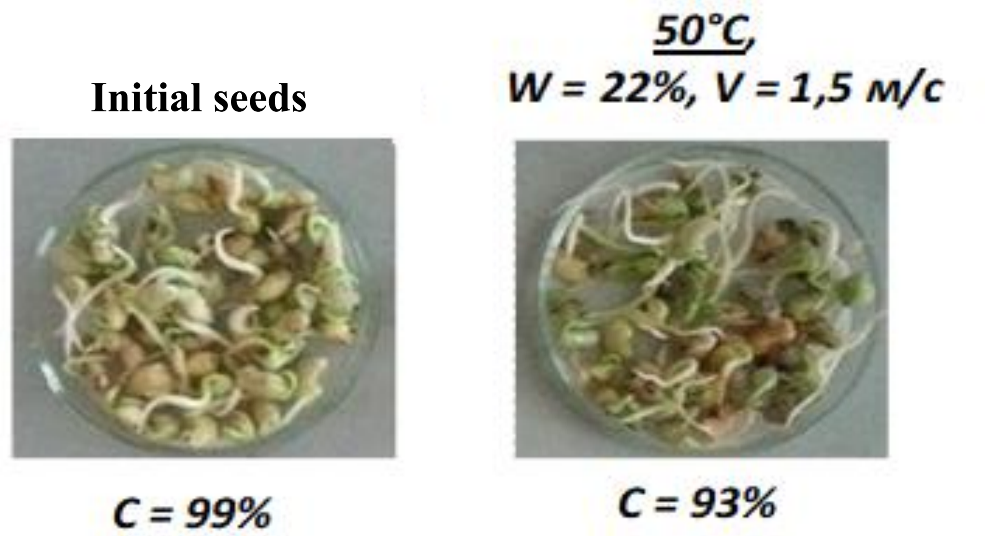


Figure 6 Photos comparing the germination of soybean seeds of the "Kniazhna" variety on the 7th day of germination.

For the statistical assessment of soybean seed germination, a study of the influence of three factors was conducted: heat carrier temperature, heat carrier velocity, and initial seed moisture. The results of the three-factor experiment by orthogonal compositional plan of the second order, made it possible to obtain the quadratic regression equation in the code variables for the germination response following the drying process:

$$\overset{\frown}{y} = 78 - 27x_1 - 0.86x_2 - 16.14x_3 - 11.73x_1^2 - 0.17x_2^2 - 2.21x_3^2 - 0.125x_1x_2 - 15.625x_1x_3 + 0.125x_2x_3. \quad (3)$$

Table 6 Determination of the significance of regression coefficients.

a_i, a_{ii}, a_{ij}	S_{ai}, S_{aii}, S_{aij}	t_{ip}
$a_0 = 78$	0.41	190.2
$a_1 = 27$	0.19	142.2
$a_2 = -0.86$	0.19	4.53
$a_3 = -16.14$	0.19	84.94
$a_{11} = -11.73$	0.3	39.1
$a_{22} = 0.17$	0.3	0.57
$a_{33} = -2.21$	0.3	7.36
$a_{12} = -0.125$	0.22	0.57
$a_{13} = -15.625$	0.22	71.05
$a_{23} = 0.125$	0.22	0.57

In the resulting equation, the estimates of the coefficients $a_{12} = -0.125$, $a_{22} = 0.17$, and $a_{23} = 0.125$ were found to be insignificant. The coefficients a_{12}, a_{22}, a_{23} are excluded from the regression equation.

Then the regression equation takes the form:

$$\overset{\frown}{y} = 78 - 27x_1 - 0.86x_2 - 16.14x_3 - 11.73x_1^2 - 2.21x_3^2 - 15.625x_1x_3. \quad (4)$$

The given regression equation indicates that the two most significant factors affecting soybean germination are the heat carrier temperature and the initial seed moisture.

Let us check the correctness of the resulting regression equation. For this purpose, the factor values x_i corresponding to the first row of the experiment are assigned. Thus:

$$\hat{y} = 78 - 27(-1) - 0.86(-1) - 16.14(-1) - 11.73(+1) - 2.21(+1) - 15.625(+1) = 92.45.$$

The estimate of the variance of inadequacy is calculated using the formula (5):

$$S_{inad}^2 = \frac{1}{N-r}\sum_{j=1}^{N}(\overline{y_j} - \hat{y}_j)^2 = \frac{1}{15-7}\cdot 1.27 = 0.16.$$

The adequacy of the mathematical model is checked by the experimental results using F the Fisher criterion:

$$F_p = \frac{S_{inad}^2}{S_y^2} = \frac{0.16}{1.2} = 0.13.$$

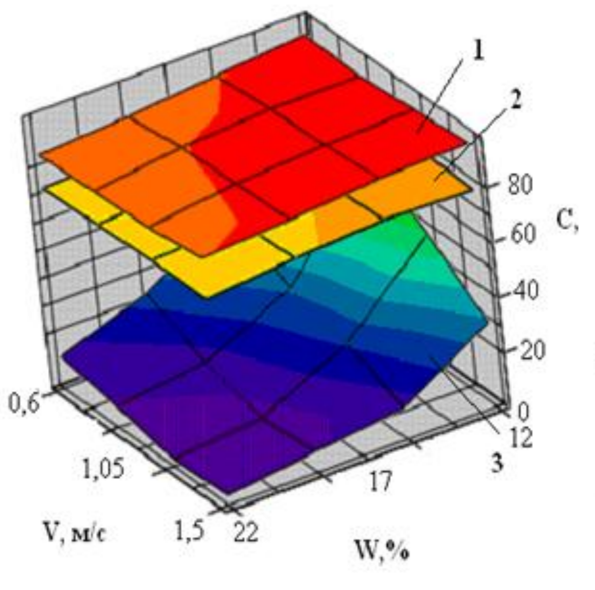
For the number of degrees of freedom $v_2 = N - r = 8$ and $v_1 = N(m-1) = 30$ and the level of significance, $p = 0.05$ the critical value of the Fisher statistic is determined from the tables $F_{cr} = 2.27$. Since $F_p = 0.13 < F_{cr} = 2.27$, then the mathematical model in the form of a quadratic regression equation is adequate to the real object.

Let us now transform the quadratic regression equation from coded factors x_i to the corresponding physical values:

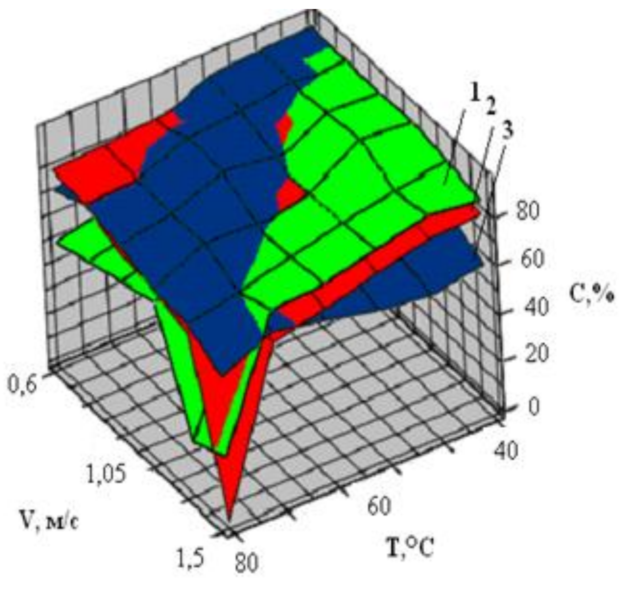
$$C = 78 - 27\cdot\left(\frac{t-65}{15}\right) - 0.86\cdot\left(\frac{V-1{,}05}{0{,}45}\right) - 16.14\cdot\left(\frac{W-17}{5}\right) - 11.73\cdot\left(\frac{t-65}{15}\right)^2 - -2.21\cdot\left(\frac{W-17}{5}\right)^2 - 15.625\cdot\left(\frac{t-65}{15}\right)\cdot\left(\frac{W-17}{5}\right). = \quad (5)$$
$$= 267.4 + 1.6\cdot t - 1.91\cdot V + +10.32\cdot W - 0.052\cdot t^2 - 0.088\cdot W^2 - 0.21\cdot t\cdot W$$

Analysis of the obtained similarity equation shows that in the temperature range from 40 to 60ºC the determining factor is the heat carrier temperature. The most significant similarity is observed at a heat carrier temperature of 50ºC.

According to the obtained regression equation for soybean seed germination after drying in the elementary layer, response surfaces from the action of three factors were found, which were constructed in the Mathcad 15 graphics program (Figure 7).



a)



b)

Figure 7 Response surfaces of soybean seed germination after drying in an elementary layer for the action of the temperature and initial humidity.
Note: a) temperature: 1 – 40ºC, 2 – 60ºC, 3 – 80ºC; b) initial humidity: 1 – 12%, 2 – 17%, 3 – 22%.

Analysis of the germination surfaces (Figure 7) reveals that, within the temperature range of 40 to 60 °C, the determining factor is the coolant temperature, as the response surfaces exhibit a linear character. The greatest germination is observed at a coolant temperature of 40ºC. An increase in temperature to 80ºC leads to a sharp decrease in soybean seed germination, especially in the area of high material humidity.

In the present study, a comprehensive investigation of soybean seeds as an object of drying was conducted, combining studies of physico-mechanical, thermophysical, heat and mass transfer, and kinetic characteristics (studies by different authors provide only one of the listed properties of soybeans).

All the research conducted in the above article can be divided into the following parts by direction:

- analysis of literature studies and conducted own experimental studies, which indicate the peculiarity of soybeans as an object of drying and confirm the experimental data of other researchers, and also contain other results that have not been studied. These include physico-mechanical and thermophysical properties;
- own experimental studies. These include the determination of heat and mass transfer and kinetic characteristics.

It can be noted that when calculating the heat and mass transfer characteristics given in Table 4, various properties of soybean seeds were used, such as physico-mechanical, thermophysical, and kinetic characteristics, which were determined through the author's own research.

The results of the three-factor experiment based on a second-order orthogonal composite plan enabled the derivation of a quadratic regression equation for soybean seed germination, with a significance level of $p = 0{,}05$ The adequacy of the mathematical model to the real object was tested by the critical value of the Fisher criterion. The value of the approximation reliability is R^2=0.98. The results obtained on the physico-mechanical properties of soybean seeds of the Kniazhna variety confirm the trends identified in previous studies. In particular, an increase in seed moisture content leads to an increase in its size, mass, and volume, which is consistent with the data of studies of different soybean varieties, where an increase in the length, width, and thickness of the seeds with increasing moisture content was observed **[1]**. It was also noted that with increasing moisture content, the compressive strength of the seeds decreases, which is associated with increased tissue deformability **[2]**.

Determination of the heat capacity of soybean seeds in the temperature range from 32.5 to 92.5°C showed an increase in this indicator with increasing temperature, which corresponds to well-known patterns for biological materials **[3]**, and **[16]**. The thermal conductivity coefficient also increases with increasing temperature and humidity, which is confirmed in studies of the thermophysical properties of soybeans **[19]**. These data are important for modelling drying processes and optimising heat treatment modes.

Studies on the kinetics of soybean seed drying have shown that increasing the temperature of the heat carrier from 40 to 60°C results in a corresponding increase in the drying rate, from 0.28%/min to 0.46%/min. This is consistent with the results of other studies **[11]**, which indicate that increasing the drying temperature contributes to the intensification of the process but can negatively affect seed quality **[5]**, and **[6]**. In particular, at a drying temperature of 70 °C, a significant decrease in seed germination was observed, while at 50°C high germination and germination energy are maintained **[13]**, and **[20]**.

The results of the study confirm that the optimal drying regime for maintaining high germination of soybean seeds is a heat carrier temperature of 50°C, at which germination is 93% **[27]**. This is consistent with the data of other authors who recommend drying temperatures in the range of 40-50°C to maintain the physiological quality of seeds **[20]**. In particular, at a temperature of 50°C, the optimal combination of drying speed and seed viability preservation is observed **[21]**.

In the study **[28]**, the negative impact of increased drying temperatures on the physiological quality of sweet sorghum seeds was recorded. The authors found that seed germination decreases with increasing temperature, especially when the temperature exceeds 40°C, with each subsequent increase in temperature leading to a decrease in germination of approximately 0.5%.

As indicated **[5]**, **[29]**, this trend is attributed to the increase in the moisture removal rate (WRR) from seeds under the influence of high drying air temperatures. Accelerated dehydration leads to a significant moisture gradient between the seed's surface and internal tissues, causing the formation of microcracks in the cotyledons and damage to the shell, which in turn worsens the seed's physiological quality.

Such structural defects may also contribute to the development of latent damage or even increase the risk of seed spoilage, which negatively affects its storage and overall seeding potential **[30]**.

The negative impact of high-temperature drying on the physiological quality of soybean seeds was documented **[31]**, who found that temperatures above 40°C cause damage to cell structures, in particular membrane destruction and loss of soluble substances, especially in the embryonic axis zone. Such damage adversely affects seedling development and, accordingly, leads to a decrease in two key indicators of seed viability - germination and germination energy.

The study **[32]** emphasizes that the preservation of the physiological potential of soybean seeds depends not only on the drying regime, but also on the initial quality of the seed material and storage conditions. In particular, seeds with an intact structure are less prone to a decrease in shell thickness when stored both in a favorable environment (10°C) and under conditions that may worsen the physiological state (25°C).

In a study conducted by **[33]**, the relationship between energy consumption and the physiological properties of soybean seeds under periodic drying conditions was analyzed. Seed quality assessment included parameters such as germination, germination energy and the presence of cracks, as well as the amount of energy required for the drying process. The results of the work showed that periodic drying at a temperature of 50°C allows reducing energy consumption by almost 46% compared to conventional modes. At the same time, a temperature of 70°C significantly impaired the quality of the seeds, resulting in a sharp decrease in their germination and vigor, which indicates accelerated physiological aging and degradation of the seed material.

It is known that in continuous drying systems, to achieve complete dehydration of seeds in one cycle of their passage through the drying chamber, it is necessary to either increase the temperature of the drying medium or increase the time the seeds spend in the chamber **[34]**, **[8]**, and **[35]**. However, excessive heat load can negatively affect the morphological integrity of seed structures, which, as established **[8]**, **[36]**, leads to a decrease in germination and germination energy.

Soybean seeds dried at a temperature of 80°C, both immediately after drying and during storage, were unable to form normal shoots, which indicates the harmful effect of high temperatures on the quality of soybean seeds **[37]**.

The periodic drying mode has proven to be an effective alternative to traditional continuous drying, offering energy savings and improved preservation of seeds both externally and internally. The use of this method allowed for a significant reduction in energy consumption: by 46% at an air temperature of 50°C and by 42% at a temperature of 70°C compared to the standard drying mode **[13]**. In addition, periodic drying with a temperature peak of 50°C contributed to the preservation of the physiological integrity of the seeds, both external structures and internal tissues. However, at a temperature of 70°C, a deterioration in the main indicators of seed quality was observed: a decrease in germination and germination energy, which, in turn, indicates an acceleration of spoilage processes and loss of viability of soybean seeds.

As part of the conducted studies **[38]**, the efficiency of soybean seed drying was evaluated using two different methods: a fluidized bed (FBD) and a fluidized bed with microwaves (MFBD). For the FBD method, the effect of drying air temperature (within 30–50°C) and air velocity (1–7 m/s) on the characteristics of the drying process and physiological indicators of seed quality, in particular the germination energy index, the level of cracking, the degree of shell damage and its hardness, was analyzed. Calculations were performed using the response surface method.

The MFBD method investigated the effect of air temperature and microwave power levels on drying kinetics and seed quality indicators, at a fixed air velocity of 7 m/s.

The results show that both methods provided a high level of seed germination (over 77%) and a low percentage of damage in the form of cracks (less than 20%). At the same time, an increase in germination time was observed, which was reflected in a decrease in the germination energy index. In addition, drying led to significant structural damage to the seed coat, particularly the formation of cracks in almost 100% of the samples, and a decrease in its hardness.

The authors **[39]** compared conventional fluidized-bed drying of soybeans with microwave fluidized-bed drying. The use of microwave technologies and a fluidized bed resulted in a 83.39–98.07% reduction in drying time and a 82.07–95.22% reduction in specific energy consumption, while reducing the soybean moisture content from 18.32% to 12%. These studies indicate the potential of using microwave technologies for drying soybean seeds. The use of microwave drying, presented in the article **[40]**, is environmentally safe, since the seeds do not come into direct contact with gas combustion products, which deteriorate its quality due to the possible penetration of carcinogenic components into the product.

The results obtained have practical significance for developing effective drying regimes for soybean seeds. In particular, it is recommended to use a heat carrier temperature of 50°C to achieve an optimal balance between drying speed and seed germination preservation. It is also important to consider the physico-mechanical and thermophysical properties of seeds when designing drying equipment and selecting drying regimes.

CONCLUSION

The analysis of soybean properties conducted by various authors, along with the findings of the author's own research, most effectively characterises soybean seeds as an object of scientific study.

With an increasing moisture content of soybean seeds, the geometric dimensions of the seeds increase by 4 to 10% for every 1% increase in moisture content.

The determination of the heat capacity of soybean seeds indicates an increase in the amount of heat required to raise the temperature of 1 kg of soybeans by one degree Kelvin, corresponding to an increase in the temperature of the coolant. At a coolant temperature of 50°C, the heat capacity of soybeans is 2000 J/kg K.

As a result of statistical analysis: a regression equation was obtained for soybean seed germination at a significance level of p=0.05, the adequacy of the mathematical model to the real object was checked by the critical value of the Fisher criterion. The value of the approximation reliability is R2=0.98.

For a graphical representation of the regression model, response graphs were constructed showing the action of three factors and their influence on soybean seed germination.

The intensity of the drying process of soybean seeds is achieved by increasing the temperature of the heat carrier, and preserving the seed properties of the material requires the introduction of low-temperature drying modes. An increase in temperature from 40 to 60°C intensifies the drying process 2.125 times. The resulting soybean seeds are characterized by a germination rate of 90-96%, which decreases with increasing temperature.

The intensity of the process and the choice of the heat carrier temperature during the drying process are determined by the soybean seed germination parameter, i.e. the manufacturer determines the heat carrier temperature depending on the possibility of seed material losses. A drying regime of 50°C has been recommended, which has an acceptable intensity and germination of soybean seeds.

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