UDC 631.867:66.047.37
DOI: 10.37128/2520-6168-2025-4-2

DETERMINATION OF RATIONAL MODE PARAMETERS FOR DRYING WALNUTS IN A CONVECTION-VIBRATION DRYER

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The results of the study on determining the rational operating parameters of drying walnuts of the Chandler variety in a convective-vibratory dryer are considered. The feasibility of using vibration effects to increase the intensity of heat and mass transfer and reduce specific energy consumption is substantiated. The material of the study was fully ripe nuts, which were dried to standard humidity. An analytical regression equation was established that describes the dependence of specific energy consumption on the temperature of the drying agent, air flow velocity and vibration acceleration of the drying chamber. The response surfaces were analyzed and the relationships between the main process factors were determined.

According to the results of mathematical modeling, rational parameters were established: temperature 38 °C, speed 22.5 m/s, vibration acceleration 65.6 m/s² at an amplitude of oscillations of 6.5 mm. Verification of the model showed that the discrepancy between theoretical and experimental data does not exceed 11%, which confirms its adequacy.

It is noted that the use of vibration effects contributes to the formation of a fluidized bed, reducing aerodynamic resistance and increasing the heat transfer coefficient. The results obtained can be used to optimize the operating parameters of laboratory and industrial dryers, develop energy-saving technologies and ensure stable quality of finished products. Prospects for further research related to modeling of drying agent turbulization and scaling processes in industrial conditions are outlined.

The proposed approach creates prerequisites for scaling the convective–vibratory drying technology to industrial conditions while maintaining product quality and significantly reducing overall energy consumption.

Key words: *convective-vibrational dryer, walnuts, heat transfer, vibration acceleration, energy efficiency, fluidized state, operating parameters, drying intensification, mathematical modeling, specific energy consumption.*

Eq. 4. Fig. 4. Table. 1. Ref. 15.

1. Problem formulation

Modern walnut production requires the introduction of efficient and energy-saving drying technologies that ensure stable product quality and compliance with agrotechnical standards. In traditional convective dryers, the drying process is characterized by high energy consumption and insufficient heat and mass transfer intensity due to the uneven distribution of nuts in the layer and the formation of local areas of aerodynamic resistance [1-5]. The use of convective-vibration dryers allows to increase the efficiency of the process by creating pseudoplastic state of the nut layer, reduction of aerodynamic drag, and intensification of heat and mass transfer [6, 7].

However, for the practical implementation of this approach, it is critically important to determine the rational operating parameters of drying – the temperature and speed of the drying agent, the amplitude and

Article received 24.10.2025. Article accepted 08.12.2025. Article published 25.12.2025.

frequency of vibrations, as well as vibration acceleration. Optimization of these parameters ensures minimal energy consumption for the drying process, which includes the costs of air heating, fan operation, and vibration. A scientifically based choice of operating modes for a convective-vibration dryer allows for increased energy efficiency and quality of the final product, which makes this research particularly relevant for the agro-industrial complex and the food industry

2. Analysis of recent research and publications

In scientific studies dedicated to post-harvest processing of walnuts, drying is considered a crucial technological stage that significantly affects the preservation of the physical-mechanical, biochemical, and consumer properties of the kernel [1, 2]. As a drying object, the walnut is characterized by a complex multilayer structure, a hard shell, and a high lipid content in the kernel, which makes the product highly sensitive to temperature effects and complicates the heat and mass transfer process [3]. An analysis of the literature sources indicates that during convective drying of walnuts, the falling-rate period predominates, in which the moisture removal intensity is limited by the internal diffusion of moisture from the kernel through the shell to the outer surface [1]. At the same time, increasing the temperature of the drying agent promotes the growth of the effective diffusion coefficient; however, exceeding the rational temperature limits leads to a deterioration in the quality of the kernel, in particular darkening, a decrease in the oxidative stability of fats, and loss of flavor properties.

In this regard, considerable attention in research is devoted to intensifying the drying process of walnuts by improving hydrodynamic conditions and applying additional physical effects. In particular, the use of vibrational impact in convective dryers is considered an effective means of increasing the intensity of heat and mass transfer [5, 7]. Vibration contributes to the destruction of the compacted layer of nuts, the formation of a pseudo-fluidized state, the reduction of temperature and humidity gradients in the material layer, and the improvement of heat and mass transfer conditions on the shell surface. It has been established that the use of convective-vibration modes allows reducing the drying time of walnuts and lowering specific energy consumption without deteriorating the quality indicators of the kernel [7].

A separate line of research is devoted to the mathematical description of the walnut drying process, taking into account their geometric and structural heterogeneity [1, 6]. The proposed models are based on solving the transient heat conduction and moisture diffusion equations for the 'shell – kernel' system and allow for assessing the impact of drying agent temperature, air flow rate, and process duration on the temperature state and moisture content of the kernel. At the same time, the literature analysis shows that the issue of determining the rational regime parameters for drying walnuts in convective-vibrational dryers, taking into account the combined effects of temperature, aerodynamic, and vibrational factors, remains insufficiently studied and requires further theoretical and experimental justification.

3. The purpose of the article

The purpose of the study is to determine the rational operating parameters for drying walnuts in a convective-vibration dryer in order to ensure minimum energy consumption and obtain a high-quality product.

To achieve this goal, the following tasks were set: to investigate the influence of temperature and speed of the drying agent on the efficiency of the process; to determine the role of vibration in reducing the aerodynamic resistance of the nut layer and increasing the intensity of heat and mass transfer; to conduct a multifactorial experiment and build a mathematical model of the process; to verify the adequacy of the model with experimental data and formulate recommendations for optimal drying modes.

4. Results and discussion

The material for the study was fully ripe Chandler walnuts with an initial moisture content of 28%, which were dried to a final moisture content of 10%, which meets regulatory requirements [8]. For experimental studies, a convective-vibration laboratory dryer was used, in which the key operating parameters of the drying process were varied [9, 10]: the temperature and speed of the drying agent, the amplitude and frequency of vibration oscillations, and the vibration acceleration. A fixed vibration amplitude of 6.5 mm was selected, while the vibration acceleration varied from 25 to 105 m/s² depending on the experiment mode. The levels of the factors and the intervals of their variation are given in Table 1. The temperature of the drying agent varied in the range of 30–40 °C, and the air flow velocity varied from 20 to 26 m/s. The experimental data were processed using Mathematica 12.0 software, which ensured high-precision analysis of the results obtained and their statistical processing.

To determine the rational operating parameters of the vibrating machine corresponding to minimum energy consumption, a plan for a multifactorial experiment was drawn up [11, 12]. The main optimization criterion was the total energy consumption for the drying process, which includes the energy for the fan drive, heating the atmospheric air, and creating a vibrating effect on the material layer [3, 13, 14].

Table 1

Factor levels and ranges of variation

Levels of variation	Factors		
	X_1- $t_{c.a.}$,°C	X_2-$v_{c.a.}$, м/с	X_3- α_{ω}, м/с^2
Upper level (+1)	40	26	105
Basic level (0)	35	23	65
Lower level (-1)	30	20	25
Variation interval (E)	5	3	40

The temperature and speed of the drying agent, as the main factors determining the energy efficiency of the process, varied within practically reasonable values to ensure product quality and energy efficiency of the process. The temperature of the drying agent tc.a varied from 30 °C to 40 °C in increments of 5 °C, with the upper level limited by product quality standards and the lower level by the technological feasibility of the process. The speed of the drying agent vc.a varied from 20 m/s to 26 m/s in increments of 3 m/s, which ensured overcoming the aerodynamic resistance of the nut layer and increasing the energy efficiency of drying.

An important factor affecting the intensity of heat and mass transfer is the parameter of vibration impact on the layer of nuts in the drying chamber. Most previous studies have used vibration acceleration aω as an indicator of vibration intensity [6, 15]. However, vibration acceleration is the second derivative of the amplitude of oscillations over time, and the same value can be achieved with different combinations of amplitude and frequency of oscillations. In view of this, it is advisable to fix one of the parameters, for example, the amplitude, at a reasonable level and vary the other parameter, the oscillation frequency, within the limits of design and technological constraints.

In this study, the oscillation amplitude was fixed at A = 6.5 mm, which corresponds to the capabilities of the laboratory setup, while the vibration acceleration aω varied from 25 to 105 m/s^2 in increments of 40 m/s^2. This approach allows studying the effect of different intensities of vibration on heat and mass transfer and the energy efficiency of the process without violating the design limitations of the equipment.

The experiment was planned taking into account the multifactorial influence of temperature, drying agent velocity, and vibration parameters. The experiment planning matrix and methodology are presented in [11]. The following factors were selected: X_1 – drying agent temperature tsa; X_2 – drying agent velocity vsa; X_3 – vibration acceleration $A\omega^2$; Y – optimization criterion, energy consumption – Q.

For each combination of parameters, a series of experiments was conducted with three repetitions, which allowed random errors to be taken into account and the statistical reliability of the results to be assessed. As a result, analytical dependencies of the heat transfer coefficient and specific energy consumption on the main operating parameters of the process were obtained. The studies confirmed that the use of vibration contributes to the formation of a pseudo-fluidized state of the nut layer, a reduction in aerodynamic drag, an increase in air flow turbulence, and an increase in the energy efficiency of the process.

Thus, the proposed method allows for an objective assessment of the efficiency of the walnut drying process, taking into account the combined influence of temperature, drying agent speed, and vibration parameters. The results obtained can be used to optimize the operating modes of laboratory and industrial convective-vibration dryers, as well as to develop energy-saving technologies for drying plant products with high quality of the final product.

After processing the experimental data, a regression equation was obtained, which is given in natural values:

$$Y = 14{,}266 - 0{,}286t_{ca} + 0{,}0032t_{ca}^2 - 0{,}362v_{ca} + 0{,}00158t_{ca}v_{ca} + 0{,}0061v_{ca}^2 - 0{,}0771a_{\omega} - 0{,}00425t_{ca}a_{\omega} - 0{,}0129v_{ca}a_{\omega} + 0{,}071a_{\omega}^2 \quad (1)$$

The analysis of the regression equation showed that it is adequate for the experimental data at a 5% significance level.

The response surfaces with one of the three factors fixed are shown in Figures 1-3.

The analysis of the obtained regression equation to find rational operating parameters was performed using two-dimensional intersections. The rational operating parameters of the experimental industrial model of the vibrating machine were found by analyzing the regression equation

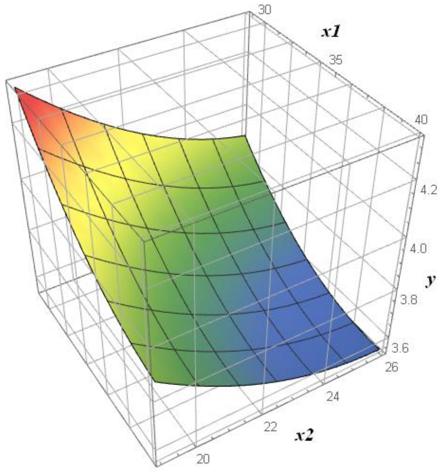

Fig. 1. Dependence of the optimization criterion on the temperature and speed of the drying agent

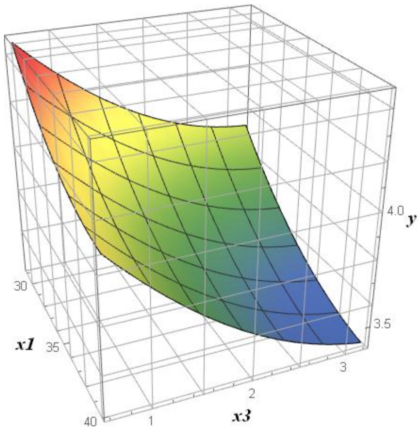

Fig. 2. Dependence of the optimization criterion on the temperature of the drying agent and vibration acceleration

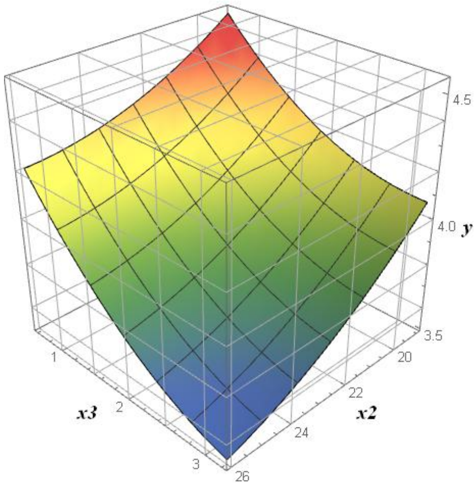

Fig. 3. Dependence of the optimization criterion on the speed of the drying agent and vibration acceleration

The analysis of the regression equation allowed us to determine the following rational parameters: drying agent temperature 38 °C, drying agent velocity 22.5 m/s, drying chamber vibration acceleration 65.6 m/s2 at a fixed amplitude of its oscillations 6.5 mm.

When conducting research to determine the rational operating parameters, a series of experiments was additionally carried out to verify the mathematical model [11]. The results of these experiments are shown in Fig. 4.

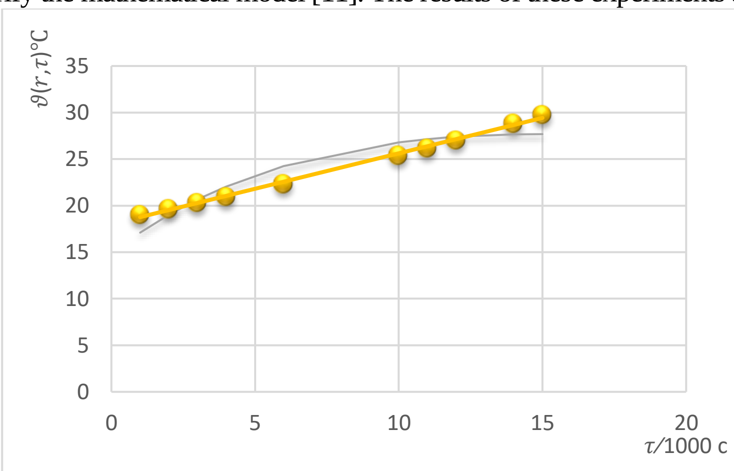

Fig. 4. Material temperature during drying at a coolant temperature of 35°C and an ambient temperature of 15°C

The theoretical curve is described by equation (2), and the experimental data are approximated by equation (3):

$$\upsilon_{т} = 18{,}188\exp(0.113\,\tau) \quad (2)$$

$$\upsilon_{exp} = 18{,}33\exp(0.11\tau) \quad (3)$$

The points on the graph correspond to experimental data, and the line is described by equation (4).

$$\theta(r,s) - \frac{\vartheta_0}{s} = \frac{\varphi_1}{\psi_1} - \frac{\varphi_2}{\psi_2} \quad (4)$$

The difference between theoretical and experimental data does not exceed 11%, which gives reason to believe that the mathematical model adequately describes the process of drying walnuts in the vibration machine developed and manufactured by us.

5. Conclusion

As a result of experiments conducted to determine the rational operating parameters for drying Chandler walnuts, an analytical regression equation was obtained that reflects the dependence of specific energy consumption on the main factors: the temperature and speed of the drying agent, as well as the vibration acceleration of the drying chamber. The constructed response surfaces made it possible to visualize the complex influence of these parameters on the energy efficiency of the process and to determine the relationships between the factors.

Analysis of the regression equation confirmed the adequacy of the obtained dependencies with the experimental data at a significance level of 5%. Based on the results of mathematical modeling and analysis of two-dimensional cross-sections of response surfaces, rational operating parameters for the vibrating dryer were determined: drying agent temperature 38 °C, air flow velocity 22.5 m/s, vibration acceleration of the drying chamber 65.6 m/s² at a fixed oscillation amplitude of 6.5 mm. The use of these parameters allows for an optimal balance between the intensity of heat and mass transfer and the minimization of energy costs for the drying process.

To verify the mathematical model, an additional series of experimental studies was conducted, the results of which were compared with the theoretical curve described by the approximation equations. It was found that the discrepancy between the theoretical and experimental data does not exceed 11%, which confirms the high level of adequacy of the developed mathematical model and its ability to accurately describe the process of drying walnuts in a convective-vibration dryer.

The results obtained allow us to conclude that the application of vibration contributes to the formation of a pseudo-fluidized state of the nut layer, a decrease in aerodynamic resistance, an increase in air flow turbulence and, as a result, an increase in the heat transfer coefficient and energy efficiency of the process. In addition, the proposed method for determining rational operating parameters, taking into account the temperature, the speed of the drying agent, and vibration parameters can be used to optimize the operation of laboratory and industrial convective-vibration dryers, as well as to develop energy-saving technologies for drying plant products with high consumer and biological properties of the final product.

Thus, the study not only confirmed the effectiveness of the combined vibration-convection effect on a layer of nuts, but also provided a scientific basis for the development of methodological recommendations for optimizing the drying process and increasing its energy efficiency on an industrial scale.

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ВИЗНАЧЕННЯ РАЦІОНАЛЬНИХ РЕЖИМНИХ ПАРАМЕТРІВ СУШІННЯ ВОЛОСЬКИХ ГОРІХІВ У КОНВЕКТИВНО-ВІБРАЦІЙНІЙ СУШАРЦІ

Розглянуто результати дослідження з визначення раціональних режимних параметрів сушіння волоських горіхів сорту «Chandler» у конвективно-вібраційній сушарці. Обґрунтовано доцільність використання вібраційного впливу для підвищення інтенсивності тепломасообміну та зниження питомих енергетичних витрат. Матеріалом дослідження були горіхи повної стиглості, які висушували до нормативної вологості. Встановлено аналітичне рівняння регресії, що описує залежність питомих енергетичних витрат від температури сушильного агенту, швидкості повітряного потоку та віброприскорення сушильної камери. Проаналізовано поверхні відгуку та визначено взаємозв'язки між основними факторами процесу.

За результатами математичного моделювання встановлено раціональні параметри: температура 38 °C, швидкість 22,5 м/с, віброприскорення 65,6 м/с² при амплітуді коливань 6,5 мм. Верифікація моделі показала, що розбіжність між теоретичними і експериментальними даними не перевищує 11 %, що підтверджує її адекватність.

Зазначено, що застосування вібраційного впливу сприяє формуванню псевдозрідженого шару, зменшенню аеродинамічного опору та підвищенню коефіцієнта теплообміну. Отримані результати можуть бути використані для оптимізації параметрів роботи лабораторних і промислових сушарок, розробки енергозберігаючих технологій та забезпечення стабільної якості готової продукції. Окреслено перспективи подальших досліджень, пов'язаних із моделюванням турбулізації сушильного агенту та масштабуванням процесів у промислових умовах.

Запропонований підхід створює передумови для масштабування технології конвективно-вібраційного сушіння до промислових умов, зберігаючи при цьому якість продукції та суттєво знижуючи загальне споживання енергії.

Ключові слова: *конвективно-вібраційна сушарка, волоські горіхи, теплообмін,* *віброприскорення, енергоефективність, псевдозріджений стан, режимні параметри, інтенсифікація сушіння, математичне моделювання, питомі витрати енергії.*

Ф. 4. Рис. 4. Табл. 1. Літ. 15.

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