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DEVELOPMENT OF A STATISTICAL MODEL FOR WALNUT SHELLING IN A RECIPROCATING MILLSTONE UNIT

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The object of this study is the process of walnut shelling in a reciprocating millstone, implementing combined compression, shear, and torsion loading. The problem being addressed is the lack of well-founded modes that simultaneously ensure complete shell destruction and a high yield of whole kernels-two conflicting requirements in processing. This study extends previous work that determined the shell fracture forces and the probabilistic nature of its failure; this work transitions from the strength characteristics of the object to machine performance.

A three-factor rotatable design of a central composite experiment (Box design) consisting of twenty trials was implemented. The factors included the angular velocity of the moving upper millstone (1.38–4.90 rad/s), the number of nut revolutions in the working channel (0.33–1.17 revolutions), and the roughness pitch of the working surfaces (7.95–18.05 mm). Two responses were recorded: shell fracture rate and whole kernel yield. Second-order regression models were obtained and tested using analysis of variance.

It was found that shell fracture rate increases with increasing angular velocity and rotational speed and decreases with increasing roughness pitch, while whole kernel yield decreases with increasing angular velocity and exhibits internal maxima at rotational speed and roughness pitch. Angular velocity is the dominant factor for both responses and serves as the main source of the tradeoff between cracking and kernel integrity. A compromise regime was identified: angular velocity of approximately 2.09 rad/s, approximately 1.0 nut revolution, and a roughness pitch of approximately 10 mm, resulting in a shell fracture rate of approximately 94.5% with a whole kernel yield of approximately 88.9%. The results serve as a basis for selecting walnut shelling machine parameters

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1. Introduction

Walnut (*Junglans regia* L.) processing is one of the most technologically complex operations in the food industry. The hard shell must be broken while preserving the relatively soft kernel as much as possible. The yield of whole, uncracked kernels directly determines the market value of the product, as crushed kernels are valued lower and lose some of their commercial value. However, incomplete shell breakage reduces the productivity of the processing line and requires reprocessing or manual reworking. Thus, walnut shelling is a process in which two conflicting technological requirements – complete shell breakage and maximum kernel integrity – must be achieved in a single operation.

Mechanically, the walnut is a composite biological system. Its shell is a thin-walled, brittle, anisotropic structure with a natural seam line (cleft), along which strength is reduced; the kernel, on the other hand, is a relatively soft body that breaks under significantly lower loads. As a result, the operating load required to break the shell is close to, and may even exceed, the load that damages the kernel. Selecting a mode that resolves this contradiction is a central engineering challenge in mechanical walnut shelling and cannot be solved by simply increasing the contact force.

In most industrial designs, the operating parameters of nut cracking machines are still selected empirically, without a quantitative description of how the kinematics of the working elements and the geometry of the working surfaces jointly affect shelling performance. This approach does not ensure a reliable balance between cracking completeness and kernel integrity and complicates the transfer of operating modes between machines and batches of raw material.

From a scientific perspective, the relevance of this topic is (is determined by) the insufficient study of the patterns of walnut shell failure under combined loading in the conditions of a real machine's working zone. Known studies typically focus separately on the strength properties of the shell, the influence of moisture, the direction of compression, or the design features of individual cracking devices. However, the quantitative relationship between the kinematic parameters of the working element, the geometry of the contact surface, and the two process responses – the degree of shell destruction and the yield of whole kernels – has been insufficiently studied. This is particularly true for units with a reciprocating millstone, where the nut is subjected not to uniaxial compression but to the combined effects of compression, shear, and torsion. Therefore, the development of a statistical model for such a process has independent scientific significance.

The study focuses on the next stage –an experimental study of the shelling process directly in a unit with a reciprocating millstone. Unlike shell strength testing, this stage utilizes the machine's process parameters: the completeness of shell destruction and the yield of whole kernels. The transition from the strength characteristics of the object to the machine's performance requires a multifactorial experiment, since the shelling result is determined simultaneously by the millstone kinematics, the length of time the nut remains in the working channel, and the geometry of the working surfaces.

Therefore, study aimed at quantitatively establishing the impact of unit operating parameters on walnut shelling performance is relevant, as it allows to move from empirical machine settings to a quantitatively substantiated selection of their operating modes.

Therefore, study aimed at quantitatively establishing the impact of unit operating parameters with a reciprocating millstone on walnut shelling performance is relevant. The scientific significance of such study lies in the development of a statistical model describing the relationship between the angular velocity of the moving millstone, the number of nut revolutions in the working channel, the roughness pitch of the working surfaces, and the shelling results. The practical significance of such study lies in the fact that the obtained patterns allow to move from empirical machine settings to a quantitatively substantiated selection of a rational operating mode that ensures a high degree of shell destruction while maintaining the integrity of the kernel.

2. Literature review and problem statement

Studies into the mechanical processing of walnuts and other nut crops can be roughly divided into two areas. The first area is concerned with the physical and mechanical properties of the shell and kernel, while the second area focuses on the development of machines and the substantiation of their operating modes. This distinction is important because knowing the shell strength alone does not solve the technological problem of shell shelling: for practical application, it is necessary to determine the machine parameters that achieve shell breakage with minimal kernel damage.

In [1], a model of the walnut shell as a spherical thin-walled shell was proposed. It was shown that this model allows one to describe the initiation and propagation of cracks in the shell under mechanical loading. However, this study is primarily focused on a theoretical explanation of the failure mechanism and does not consider the operation of specific nut shelling equipment. Therefore, the question of transitioning from the shell breakage model to the selection of machine operating modes remains unresolved.

In [2], the mechanical properties of walnuts at various cracking zones were studied using the finite element method. It has been established that the nature of the contact significantly influences stress distribution and the likelihood of kernel damage. A disadvantage of this approach is that the calculation model describes a single loading event but does not account for the repeated interaction of the nut with the working surfaces as it moves through the machine's working channel.

The authors of [3] experimentally studied the cracking characteristics of walnuts and established the dependence of the breaking force on the geometric parameters of the fruit and loading conditions. The obtained data are important for selecting a range of working forces. However, the study is limited to testing the nut as an individual object and does not demonstrate how these forces are converted into machine performance indicators – the degree of shell fracture and the yield of intact kernels.

Article [4] demonstrates the influence of humidity, deformation rate, and loading direction on the mechanical properties of walnuts. It was found that changes in humidity and compression rate can significantly alter the resistance to shell fracture. However, in an industrial machine, the nut is subjected not only to compression but also to shear, friction, and torsion. Therefore, the results of uniaxial loading require further verification under combined loading conditions. In [5], conditions enabling the production of higher-quality kernels during walnut cracking were identified. It was shown that kernel integrity depends not only on the force applied but also on the initial properties of the raw material. However, this work does not address the influence of the design parameters of the working elements, such as the surface roughness pitch and the path of the nut's interaction with the working zone.

In [6], using finite-discrete element modeling, it was shown that multi-point loading influences stress localization and crack development in the shell. This confirms the potential of distributed contact loading. However, this model does not provide a ready-made process regime for a real-world unit and does not consider the yield of intact kernels as an independent optimization criterion.

In [7], a multi-point extrusion device for cracking walnuts was developed and tested. It was shown that optimization of the design parameters allows for an increase in the proportion of cracked nuts and the yield of intact kernels. However, the design of the device differs from that of a reciprocating millstone, where destruction occurs through a combination of compression, shear, and torsion. Consequently, the obtained modes cannot be directly transferred to the unit under consideration.

In [8], the mechanical characteristics of nut destruction under impact loading were studied. It was shown that the impact direction and energy magnitude significantly influence the nature of the destruction. However, impact schemes have a drawback: as the impact intensity increases, the probability of kernel damage increases. This confirms the need to find a more controlled method of shell destruction based not on a single short-term impact, but on a controlled combined effect.

In [9], the parameters of the walnut shelling process were examined. It was found that the rotational speed of the working element significantly affects the quality of the processing. However, the object of the study is the removal of the outer skin, not the destruction of the hard shell. Therefore, the results of this study can only be used as indirect confirmation of the influence of kinematic parameters, but not as a direct justification for the shell cracking mode.

The physical and mechanical properties of various walnut varieties were studied in [10]. It was shown that size, weight, strength, and other properties depend on the variety and growing conditions. This is important for machine design; however, the study does not consider the working elements of the equipment or provide recommendations for selecting the kinematic parameters of the shelling process.

The effect of humidity and impact energy on the fracture of conophor nuts was studied in [11]. It was shown that humidity significantly influences cracking efficiency and the degree of kernel damage. However, this object differs from walnuts in geometry, shell structure, and mechanical properties. Therefore, the obtained patterns cannot be directly transferred to walnuts, but they confirm the general importance of humidity and impact energy.

The design of a cashew shelling machine was proposed in [12]. The features of mechanical separation of the kernel from the shell are demonstrated. However, cashews have a different shape and shell structure, so the design solutions for them cannot be directly applied to walnuts. At the same time, this work confirms the need to match the shape of the working element to the geometry of the fruit being processed.

The properties influencing the cracking and separation of oil palm nuts are examined in [13]. It is shown that cracking efficiency depends on the physical and mechanical properties of the raw material and the machine parameters. However, in this study, the cracking and separation process is considered for a different type of raw material, and the task of preserving the intact kernel has different technological constraints.

A cracking device for African nuts was developed in [14]. Performance and quality indicators for the machine were obtained. However, the design is based on a different fracture principle, so it does not utilize the capabilities of a reciprocating action. At the same time, this work confirms that for nut crops, cracking efficiency and kernel damage must be simultaneously considered.

A machine for cracking wild mango nuts was evaluated in [15]. It was shown that productivity and cracking quality depend on the working element parameters. However, the object and design of the machine differ from the walnut and the reciprocating millstone. Therefore, this study is useful as an analog, but does not address the problem of optimizing the operating modes for the unit in question.

A unit for cracking oil palm nuts is proposed in [16]. The study shows that increasing the intensity of mechanical action improves cracking efficiency but can degrade the quality of the separated kernel. This result is important for the problem statement, since a similar technological conflict arises during walnut husking.

In [17], the optimal moisture content for obtaining whole kernels when cracking oil palm nuts is determined. It is shown that there is a rational moisture range that ensures the best yield of whole kernels. However, this study primarily focuses on raw material moisture, while the influence of machine kinematic parameters and the geometry of the working surfaces has not been sufficiently studied.

In [18], the cracking resistance of pistachios under compressive load is studied. It is shown that the shell strength depends on the direction and conditions of force application. However, the pistachio has a natural opening and differs from the walnut in shell structure. Therefore, the results of this study cannot be directly applied, but they confirm the importance of choosing the direction and nature of loading.

In [19], the mechanical behavior of hazelnuts under compression was studied. It was found that the deformation characteristics and fracture force depend on the size and orientation of the fruit. However, the study is not related to the analysis of the machine's operation and does not consider multiple combined loading in the working channel. Therefore, it is useful for understanding the properties of the object, but does not solve the problem of choosing a shelling mode.

Patent [20] proposes a device for shelling walnuts. This technical solution is the design basis for the study under consideration. However, the patent description describes the device and operating principle, but does not contain experimentally substantiated modes linking angular velocity, the path of the nut, and the roughness pitch with the release of a whole kernel.

In a previous study, the authors [21] determined the patterns of walnut shell failure under combined loading in a system with a reciprocating millstone. It was shown that shell failure is probabilistic, and strength depends on the loading orientation and contact surface parameters. However, this study focused primarily on the strength characteristics of the shell and kernel. It did not address the problem of determining the operating mode of the system based on two indicators – the degree of shell failure and the yield of whole kernels.

Thus, an analysis of the literature shows that existing studies provide important information on shell strength, the influence of moisture content, loading direction, fruit geometry, and individual cracking machine designs. However, the problem of quantifying the operating mode of a system with a reciprocating millstone, in which walnuts are subjected to the combined effects of compression, shear, and torsion, remains unresolved. The combined effect of the angular velocity of the moving millstone, the number of nut revolutions in the working channel, and the roughness pitch of the working surfaces on two interrelated parameters – the degree of shell breakage and the yield of whole kernels – has been particularly understudied.

The reason for this unsolved problem is the complexity of the process itself: increasing the intensity of mechanical action promotes shell breakage, but simultaneously increases the likelihood of kernel damage. Therefore, simply increasing the speed or contact force is not a rational way to improve the process. To overcome this contradiction, it is advisable to use multivariate experimental design and construct regression models to determine a compromise operating mode.

All of this provides grounds for conducting an experimental study of the walnut shelling process in a reciprocating millstone unit, varying the angular velocity of the moving millstone, the number of nut revolutions in the working channel, and the roughness pitch of the working surfaces. The degree of shell breakage and the yield of whole kernels must be considered simultaneously as performance criteria, which will allow the transition from empirical machine tuning to a quantitatively substantiated choice of its operating mode.

3. The aim and objectives of the study

The aim of the study is to develop a statistical model for walnut shelling in a reciprocating millstone. This will allow to determine a rational operating mode for the shelling system that ensures sufficient shell destruction while maintaining a high whole kernel yield.

To achieve this goal, the following objectives were set:

– to obtain a regression model for the degree of shell destruction;

– to obtain a regression model for whole kernel yield;

– to construct an individual and combined desirability function based on the results of the walnut shelling experiment and determine a rational operating mode for the shelling system;

4. Materials and methods

4. 1. The object and hypothesis of the study

The object of the study is the process of shell breakage and subsequent shelling of local walnuts in a reciprocating millstone unit, which implements combined loading of compression, shear, and torsion.

The primary hypothesis of the study assumes that the unit's shell breakage performance and whole kernel yield are determined jointly by the millstone kinematic parameters and the geometry of the working surfaces. This suggests that a compromise operating mode exists that achieves sufficiently complete shell breakage and a high whole kernel yield.

This is possible because operating factors influence both performance parameters in opposite directions: parameters that intensify shell breakage simultaneously increase the risk of kernel damage.

The following assumptions were made:

– the nut in the working channel is subjected to the combined action of compression, shear, and torsion, caused by the rotational and reciprocating motion of the upper movable millstone;

– the calibrated nuts are fed into the working channel quasi-uniformly, and the raw material moisture content is fixed at approximately 12%;

– within the studied ranges of factors, each shelling parameter is a smooth function that can be adequately approximated by a second-order polynomial;

– the degree of shell destruction and the yield of whole kernels are determined by the operating parameters of the unit, and the influence of natural variability in the nuts is mitigated by preliminary calibration.

4. 2. Experimental walnut shelling unit

For the experiments, the authors developed and manufactured an experimental walnut shelling unit [20, 21]. A general view of the unit is shown in Fig. 1.

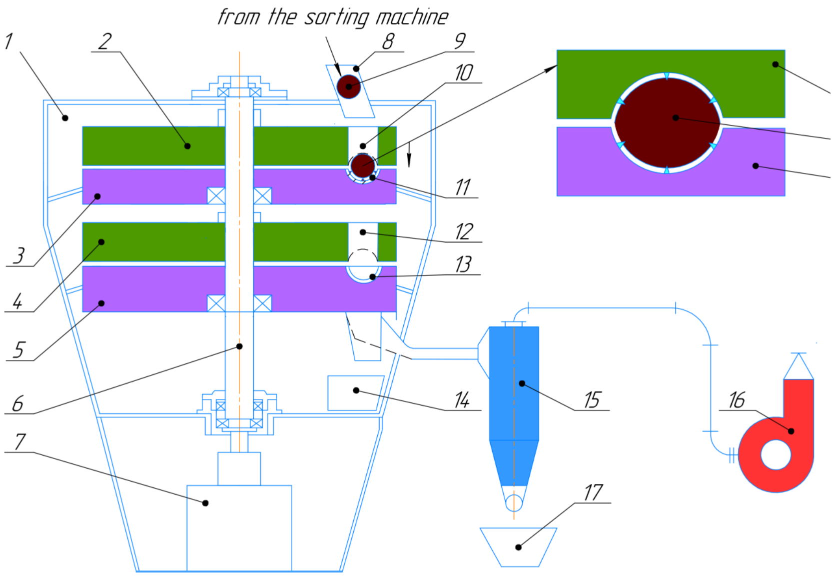
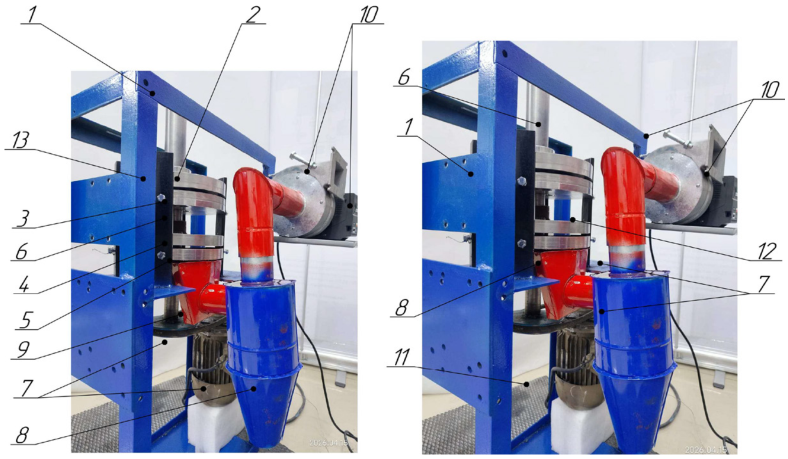


Fig. 1. Experimental setup for shelling walnuts [21]: 1 – body; 2 – upper movable millstone of the first section; 3 – lower stationary millstone of the first section; 4 – upper movable millstone of the second section; 5 – lower stationary millstone of the second section; 6 – central shaft for driving the rotary and reciprocating motion of the movable millstones; 7 – servo drive providing rotary and reciprocating motion of the movable millstones; 8 – receiving pipe for sorted walnuts; 9 – sorted (calibrated) nut; 10 – through hole in the upper movable millstone; 11 – groove with a curved trajectory; 12 – through hole in the movable millstone of the second section; 13 – groove with a curved trajectory; 14 – hopper for collecting the peeled kernel; 15 – cyclone for separating shells from the air flow; 16 – suction fan; 17 – walnut shell collection bin



a *b*

Fig. 2. Photo of the experimental setup for breaking and shelling walnuts from shells [21]: *a* — side; *b* — front; 1 — body; 2 — upper movable millstone of the first section; 3 — fixed millstone of the first section; 4 — movable millstone of the second section; 5 — fixed millstone of the second section; 6 — rotary shaft; 7 — setup drive; 8 — cyclone for separating the shell from the air flow; 9 — confuser for sucking out the hot shell from the hole of the lower millstone of the second section; 10 — suction fan and frequency converter for regulating the speed of the fan electric motor shaft; 11 — hopper for hot shell; 12 — hopper for collecting the cleaned walnut kernels; 13 — bar for attaching the fixed millstones of the first and second sections

The unit consists of a housing attached to four millstones. Each pair of millstones constitutes a section. From top to bottom, the upper millstones (2) and lower millstones (3) comprise the upper section. Millstones (4 and 5) comprise the lower millstone. The upper section, consisting of a movable upper millstone (2) and a stationary lower millstone (3), is designed to crush walnut shells. The lower section, consisting of a movable upper millstone (4) and a stationary lower millstone (5), is designed to separate the shells from the kernel. The unit operates as follows (Fig. 1, 2).

Calibrated nuts are fed through the inlet pipe 8 into the working area between two millstones. The millstones of the first section have hemispherical grooves with a curved trajectory closer to the millstone periphery. When assembled onto the shaft, these millstones form a circular shape. The surface of these grooves is roughened at varying distances. After the shell is broken in the first section, the walnuts with the broken shells pass through a through hole in the stationary millstone 3 of the first section to the second section, where the shells are separated from the kernel. For this purpose, the second section has grooves similar to those in the first section. In the second section, the surface of the groove of the upper millstone 4 is lined with a smooth, rough material. And in the lower millstone 5 of the second section, there are holes that exhaust the air flow. As the walnut reaches the lower section of the unit, the upper millstone rotates in a groove formed by the upper millstone 4 and lower millstone 5. As the millstone rotates back and forth, hot walnut particles are sucked out through openings in the lower millstone. Thus, by the time the walnut reaches the through hole in the lower millstone of the second section, the shell is completely removed, and the shelled kernels fall onto a walnut kernel collection tray. The shell particles are sucked out through a cyclone by a centrifugal fan. The shell particles settle in the cyclone, and the air flow exits through the centrifugal fan.

4. 3. Experimental procedure

Walnuts were pre-sorted (calibrated); the test material had a moisture content of approximately 12%, a shell thickness of approximately 2 mm, and an equivalent diameter of approximately 28–35 mm. Recording the moisture content and size group allowed to attribute the observed variation in shelling performance to the operating parameters of the unit, rather than to variability in the raw material.

Walnuts of a locally cultivated variety (Almaty region) with a moisture content of approximately 12% were used as raw material. A servo drive controlled the angular velocity of the upper movable millstone. The airflow velocity, i.e., the suction rate through the openings of the lower millstone (5) of the second section, was regulated by varying the speed of the centrifugal fan motor. The fan motor speed was controlled by a frequency converter. Walnuts were fed to the unit after passing through a calibration machine, where they were crushed and the walnut shells were separated from the heated shells. The shelling process was studied using a multivariate experimental design. Three operating parameters of the unit were selected as the variable factors:

x_1 – angular velocity of the movable upper millstone, ω, rad/s: 1.38–4.90;

x_2 – number of revolutions of the walnut in the working channel ν, revolutions: 0.33–1.17;

x_3 – roughness step of the working surfaces, s, mm: 7.95–18.05.

The factors were varied at five levels of the rotatable design of the central compositional experiment (Box design). The transition from natural values to coded ones was performed using the following ratios:

$$x_1 = \frac{\omega - \omega_0}{\Delta\omega}, \quad x_2 = \frac{\upsilon - \upsilon_0}{\Delta\upsilon}, \quad x_3 = \frac{s - s_0}{\Delta s}, \tag{1}$$

where ω, ν, and s – the natural values of the factors; $\omega_0 = 3.14$ rad/s, $\nu_0 = 0.75$ revolution, $s_0 = 13$ mm is the value at the center of the plane; $\Delta\omega = 1.5$ rad/s, $\Delta\nu = 0.25$ revolution, $\Delta s = 3$ mm are the variation intervals.

The variation levels of the factors are shown in Table 1.

Table 1

Factor variation levels and intervals

Planning conditions	Limits of change of factors		
	X_1	X_2	X_3
Zero level (0)	3.14	0.75	13.0
Variation interval	1.05	0.25	3.0
Upper level (+1)	4.19	1.00	16.0
Lower level (-1)	2.09	0.50	10.0
Upper star point (+1.682)	4.90	1.17	18.05
Lower star point (-1.682)	1.38	0.33	7.95

The rotatable design of the central compositional experiment for three factors includes 8 experiments of a full factorial core, 6 stellar (axial) experiments with a stellar arm length of ±1.682 and 6 experiments in the center of the plan, which in total gives $N = 20$ experiments. Repeated central experiments provide an independent estimate of the net error of the experiment and allow testing of regression models for inadequacy. In each experiment, a batch of 20 pre-calibrated nuts was processed in one pass through the working area of the unit. Two technological indicators were recorded:

Y_1 – degree of shell destruction, %, calculated as the ratio of the number of nuts whose shells are destroyed over the entire surface (with the possibility of free separation of the kernel) to the total number of nuts processed in the experiment;

Y_2 – yield of whole kernels, %, calculated as the ratio of the mass of whole, undamaged kernels to the total mass of kernels extracted in the experiment.

After each experiment, the processed material was manually sorted into fractions – completely cracked, partially cracked and uncracked nuts; whole kernels; damaged kernels and weighed on laboratory scales. The degree of destruction of the shell characterizes the completeness of the cracking effect, and the yield of the whole kernel characterizes the safety of the target product.

4. 4. Experimental planning and data processing

Experimental studies were carried out using methods of mathematical experimental planning, providing statistically valid models with a minimum number of experiments.

Processing of experimental data was carried out in the STATISTICA 10 software package (StatSoft, USA). The statistical significance of regression coefficients was assessed using the Student's test, and the adequacy of the model was assessed using the Fisher test.

Each shelling indicator was approximated by a second-order regression model in the coded factors, relation (2)

$$\begin{aligned} Y &= b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + \\ &+ b_{13}x_1x_3 + b_{23}x_2x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2, \end{aligned} \quad (2)$$

where Y – the predicted value of the shelling indicator; b_0 – free term b_1, b_2, b_3 – coefficients of linear effects; b_{12}, b_{13}, b_{23} – pairwise interaction coefficients; b_{11}, b_{22}, b_{33} – coefficients of quadratic effects.

Regression coefficients were estimated using the least squares method. The significance of the coefficients was assessed using Student's t-test, and the adequacy of the models was assessed by analysis of variance (Fisher's F test) and testing for adequacy using six central experiments. The coefficient of determination R^2, the adjusted coefficient of determination R^2, and the residual standard error were used as measures of the quality of approximation. The significance level is set to 0.05.

The compromise operating mode was determined from the obtained models in two ways: by increasing the yield of the whole kernel Y_2 while limiting the degree of shell destruction to a sufficiently high degree (Y_1 not lower than 90%) and using a combined desirability function that balances both indicators. Analysis of the response surface and search for the optimum were performed numerically within the studied range of factors.

The coefficients of regression models were determined using the least squares method. The statistical significance of the coefficients was assessed using the Student's t-test taking into account the corresponding p-values. Coefficients were considered statistically significant at a significance level of $p < 0.05$.

The quality of the experimental data approximation was assessed by the coefficient of determination R^2, the adjusted coefficient of determination R^2adj and the residual standard error. These indicators make it possible to assess the extent to which the resulting regression models describe the change in the degree of destruction of the shell Y_1 and the yield of the whole kernel Y_2 within the studied range of factors.

The adequacy of regression models was additionally assessed by the results of analysis of variance using Fisher's F test. This approach makes it possible to check whether the selected quadratic model corresponds to experimental data and whether it can be used to analyze the influence of factors and construct response surfaces.

The obtained statistical indicators were used not as an independent goal of the study, but as a means of checking the reliability of regression dependencies and justifying the choice of a rational operating mode for a unit with a reciprocating millstone.

The following simplifications were adopted in the mathematical description of the walnut shelling process. The experiments used pre-calibrated nuts of a single size group with a moisture content of approximately 12%; therefore, the influence of size heterogeneity, moisture content, and varietal differences was not specifically considered within this model. The walnut shell was treated as a fragile biological membrane, susceptible to fracture under the combined effects of compression, shear, and torsion, without a detailed description of its microstructure.

The model considered only three controllable factors: the angular velocity of the moving upper millstone, the number of nut revolutions in the working channel, and the roughness pitch of the working surfaces. The remaining setup parameters, including the gap between the working surfaces, nut feed, raw material moisture, size group, kernel condition, and aspiration parameters, were assumed constant. It was also assumed that in each experiment, the nuts passed through the working zone under comparable conditions, and the influence of the random orientation of individual nuts was accounted for through the experimental scatter of results. Second-order regression models were used as an empirical mathematical description of the process within the selected domain of factors. Therefore, the obtained relationships are applicable only within the studied ranges: angular velocity of the moving upper millstone, ω, rad/s: 1.38–4.90; walnut rotational speed in the working channel, ν, rpm: 0.33–1.17; roughness pitch of the working surfaces, s, mm: 7.95–18.05. Outside these ranges, the use of models for prediction requires additional experimental verification.

5. Results of the walnut shelling process study in an experimental setup

5. 1. Regression model for the degree of shell breakage

To determine rational parameters for the process of shell breakage and kernel separation, studies were conducted using a rotatable experimental design method, which allows for the most accurate mathematical description of the process.

The design matrix for the rotatable design of the central compositional experiment and the resulting shelling parameter values are presented in Table 2.

Table 2

Design matrix for the rotatable design of the central compositional experiment

Experiment	x_1	x_2	x_3	ω, rad/s	ν, rev	s, mm	Y_1	Y_2
1	1	1	1	4.19	1.00	16.0	82.2	72.5
2	1	1	–1	4.19	1.00	10.0	95.9	71.8
3	1	–1	1	4.19	0.50	16.0	89.1	73.3
4	1	–1	–1	4.19	0.50	10.0	88.8	72.5
5	–1	1	1	2.09	1.00	16.0	87.6	82.7
6	–1	1	–1	2.09	1.00	10.0	94.5	88.9
7	–1	–1	1	2.09	0.50	16.0	82.8	74.2
8	–1	–1	–1	2.09	0.50	10.0	88.9	83.3
9	–1.682	0	0	1.37	0.75	13.0	85.1	81.8
10	1.682	0	0	4.91	0.75	13.0	83.9	79.8
11	0	–1.682	0	3.14	0.33	13.0	74.5	76.5
12	0	1.682	0	3.14	1.17	13.0	95.7	75.7
13	0	0	–1.682	3.14	0.75	8.0	86.3	81.9
14	0	0	1.682	3.14	0.75	18.0	84.8	78.5
15	0	0	0	3.14	0.75	13.0	90.5	80.2
16	0	0	0	314	0.75	13.0	90.4	80.4
17	0	0	0	3.14	0.75	13.0	90.1	80.6
18	0	0	0	3.14	0.75	13.0	90.7	80.8
19	0	0	0	3.14	0.75	13.0	90.8	79.6
20	0	0	0	3.14	0.75	13.0	90.9	80.5

Regression model for the degree of shell damage Y_1.

The second-order full quadratic model in coded factors has the form (3)

$$Y_1 = 90.44 + 0.01x_1 + 3.39 \cdot x_2 - 2.12 \cdot x_3 - 1.28 \cdot x_1 x_2 - \\ -0.05 \cdot x_1 x_3 - 1.85 \cdot x_2 x_3 - 1.30x_1^2 - 1.09x_2^2 - 0.93 \cdot x_3^2. \quad (3)$$

The regression coefficients for Y_1 are shown in Table 3.

Table 3

Regression coefficients for Y_1

Model term	Coefficient	Standard error	t-value	p-value	Evaluation
b_0	9.438	1.749	51.70	<0.001	significant
x_1	0.013	1.161	0.01	0.991	insignificant
x_2	3.387	1.161	2.92	0.015	significant
x_3	–2.118	1.161	–1.82	0.098	trend
x_1x_2	–1.275	1.516	–0.84	0.420	insignificant
x_1x_3	–0.050	1.516	–0.03	0.974	insignificant
x_2x_3	–1.850	1.516	–1.22	0.250	insignificant
x_1^2	–1.299	1.130	–1.15	0.277	insignificant
x_2^2	–1.087	1.130	–0.96	0.359	insignificant
x_3^2	–0.928	1.130	–0.82	0.431	insignificant

Table 3 shows that the number of walnut revolutions in the milling channel has the greatest positive effect on the degree of shell breakage. This demonstrates that the completeness of shell breakage is determined largely by the duration and route of contact between the nut and the milling surfaces, rather than by a simple increase in millstone speed. The roughness pitch of the milling surfaces has a negative effect: increasing the distance between roughness elements reduces the number of local contact zones, which reduces the intensity of shell cracking. The effect of angular velocity on Y_1 is weaker according to current data, indicating the need to combine speed, contact time, and surface geometry.

The number of walnut revolutions in the milling channel x_2 has the most pronounced effect on the degree of shell breakage. The positive regression coefficient indicates that increasing this factor increases the degree of shell breakage. Since the p value of 0.015 is less than 0.05, the effect of this factor can be considered statistically significant.

5. 2. Regression model of the whole kernel output

The second-order full quadratic model for the whole kernel output has the form (4)

$$Y_2 = 80.40 - 3.10x_1 + 0.82 \cdot x_2 - \\ -1.43 - x_3 - 1.95 \cdot x_1 x_2 + 2.10 \cdot x_1 x_3 + \\ +0.35 \cdot x_{12} x_3 - 0.17x_1^2 - 1.83x_2^2 - 0.38x_3^2. \quad (4)$$

The regression coefficients for the entire Y_2 kernel output are presented in Table 4.

Table 4

Regression coefficients for Y_2

Model term	Coefficient	Standard error	t-value	p- value	Evaluation
b_0	80.4	1.175	68.42	<0.001	significant
x_1	–3.102	0.780	–3.98	0.003	significant
x_2	0.825	0.780	1.06	0.315	not significant
x_3	–1.429	0.780	–1.83	0.097	trend
x_1x_2	–1.950	1.019	–1.91	0.085	trend
x_1x_3	2.100	1.019	2.06	0.066	trend
x_2x_3	0.350	1.019	0.34	0.738	insignificant
x_1^2	–0.169	0.759	–0.22	0.829	insignificant
x_2^2	–1.830	0.759	–2.41	0.037	significant
x_3^2	–0.381	0.759	–0.50	0.627	not significant

Table 4 shows that the whole kernel yield Y_2 is most sensitive to the angular velocity of the moving upper millstone. Increasing angular velocity leads to a decrease in whole kernel yield, as the intensity of mechanical impact increases and the likelihood of kernel damage after shell breakage increases. The significant quadratic effect of the nut's rotation rate indicates the existence of a rational region for this factor: with an insufficient number of rotations, the shell is not completely broken, while with an excessive number of rotations, the already cracked nut continues to be subject to mechanical impact, which reduces the kernel's safety.

Response surfaces were constructed using the rotatable central composite design data. Y_1 – the degree of shell breakage, %, Y_2 – the whole kernel yield, %. For reference: $R^2\text{adj}(Y_1) = 0.283$, $R^2\text{adj}(Y_2) = 0.570$.

Fig. 3–8 show the graphical dependences of the degree of shell destruction on the angular velocity and the number of revolutions of the nut (Fig. 3), the dependence of the degree of shell destruction on the angular velocity and the number of roughness steps (Fig. 4), the dependence of the degree of shell destruction on the number of revolutions of the nut and the roughness step (Fig. 5), the dependence of the yield of the whole kernel on the angular velocity and the number of revolutions of the nut (Fig. 6), the dependence of the yield of the whole kernel on the angular velocity and the roughness step (Fig. 7), the dependence of the yield of the whole kernel on the number of revolutions of the nut and the roughness step (Fig. 8).

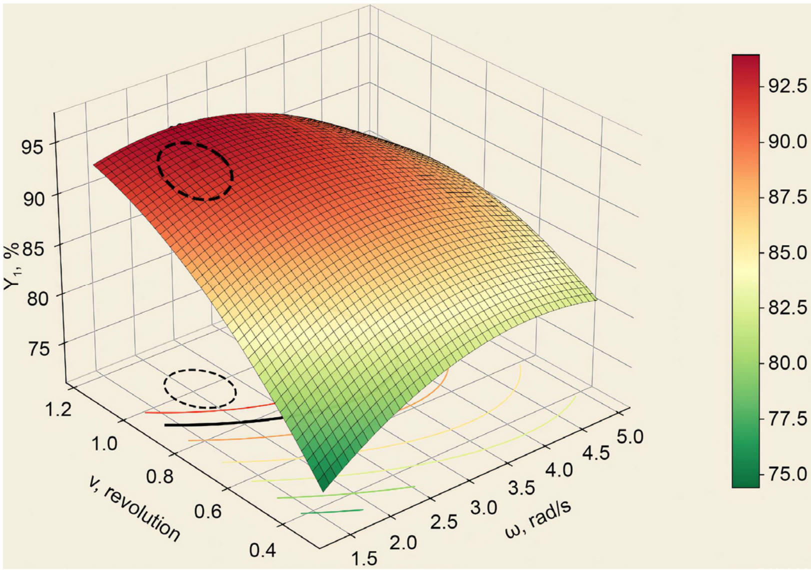


Fig. 3. Dependence of the degree of shell fracture Y_1 on the angular velocity ω and the number of nut revolutions ν at $s=13$ mm

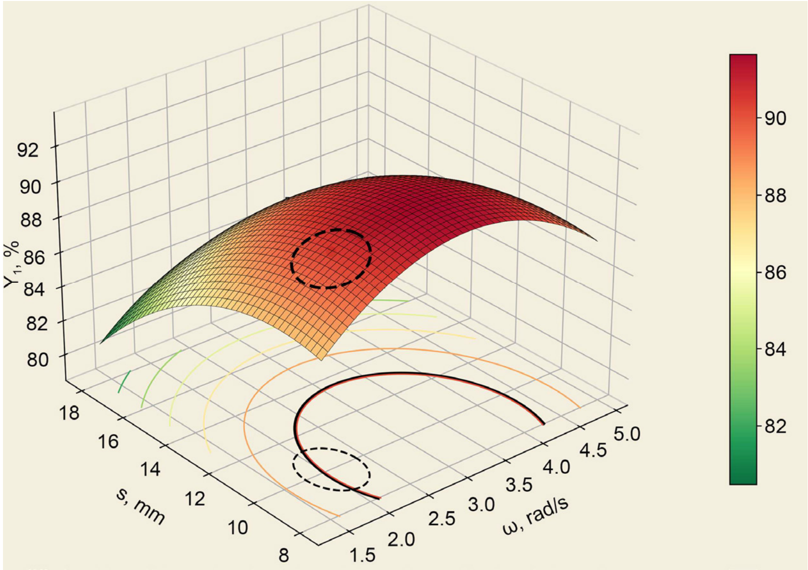


Fig. 4. Dependence of the degree of shell fracture Y_1 on the angular velocity ω and the roughness step s at $\nu=0.75$ rev.

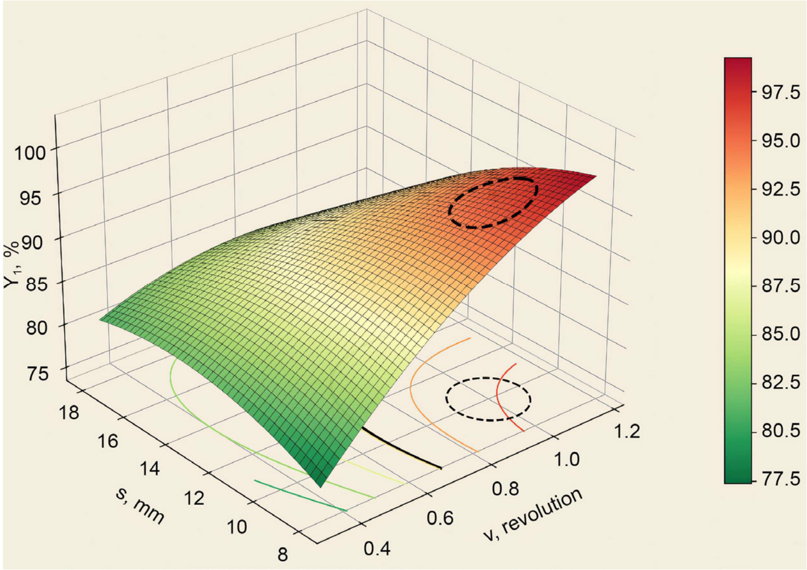


Fig. 5. Dependence of the degree of shell fracture Y_1 on the number of nut revolutions ν and the roughness step s at $\omega=3.14$ rad/s

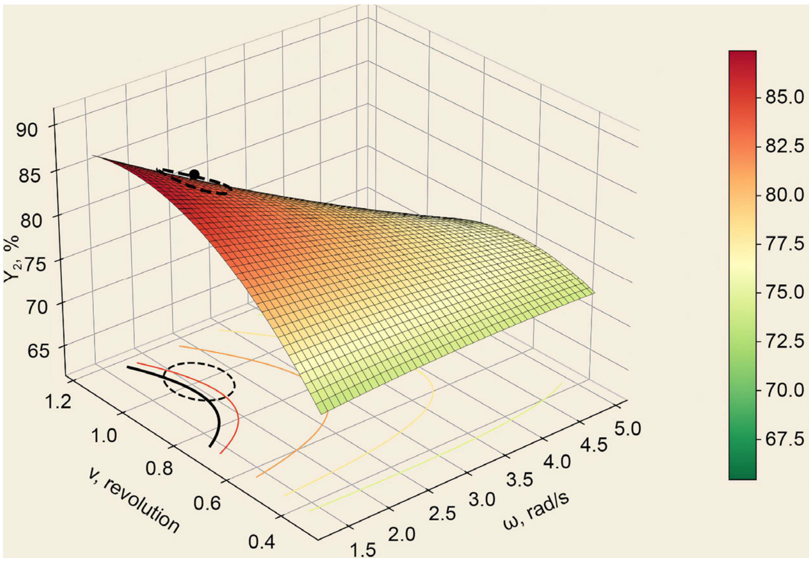


Fig. 6. Dependence of the intact kernel yield Y_2 on the angular velocity ω and the number of nut revolutions ν at $s = 13$ mm

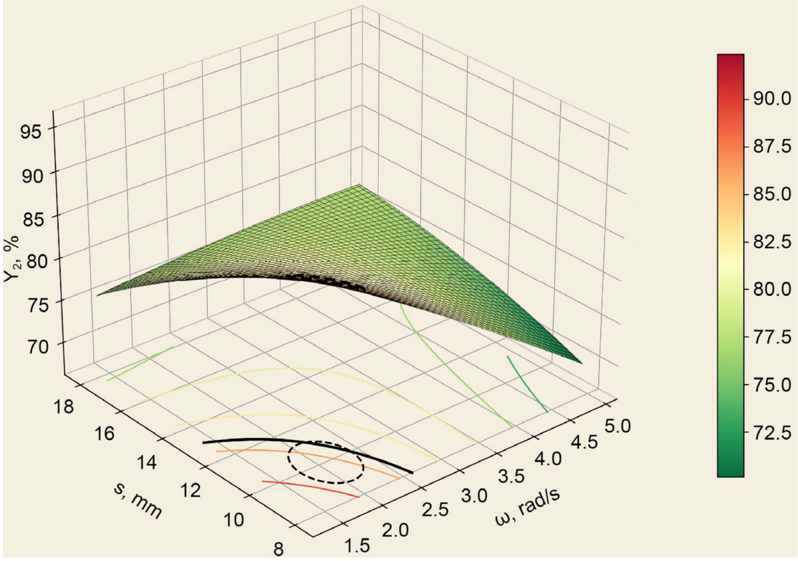


Fig. 7. Dependence of the intact kernel yield Y_2 on the angular velocity ω and the roughness step s at $\nu = 0.75$ rev.

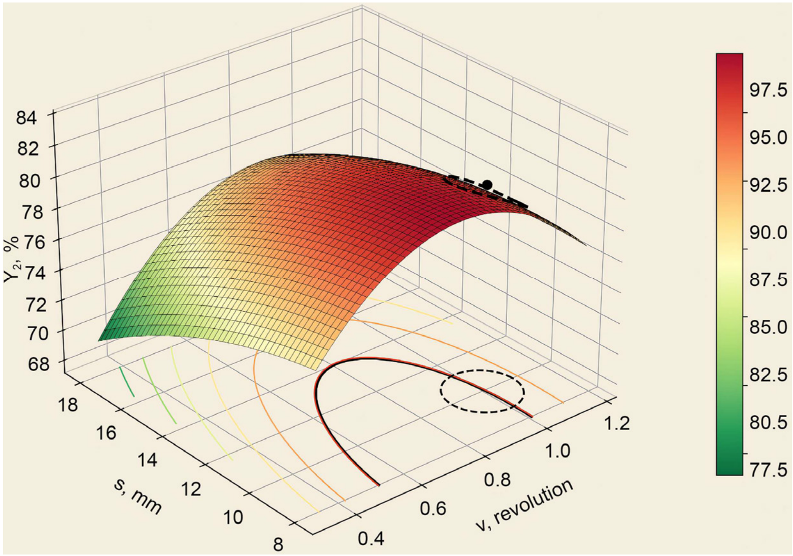


Fig. 8. Dependence of the yield of the whole kernel Y_2 on the number of revolutions of the nut ν and the roughness step s at $\omega = 3.14$ rad/s

The resulting response surfaces showed that the degree of shell destruction and the yield of whole kernels vary differently under the influence of these factors.

5. 3. Constructing a desirability function based on the results of a walnut shelling experiment

The Derringer-Suwich method was used to determine the optimal operating mode for the setup. Unlike single-response experiments, two process parameters were considered for the walnut shelling process: Y_1 – the degree of shell destruction, in %, and Y_2 – the yield of whole kernels, in %. Both parameters should be maximized.

For Y_1, the process limits $L_1 = 80\%$ and $U_1 = 100\%$ were adopted. For Y_2, the limits $L_2 = 65\%$ and $U_2 = 100\%$ were adopted. These limits allow to evaluate the quality of each experiment without artificially assigning zero or one desirability to most observations.

Individual desirability functions were calculated using the linear form (5), (6):

$$d_1 = \frac{(Y_1 - L_1)}{U_1 - L_1}, \tag{5}$$

$$d_2 = \frac{(Y_2 - L_2)}{U_2 - L_2}. \tag{6}$$

If the response value is below the lower bound, $d = 0$ is assumed; if above the upper bound, $d = 1$ is assumed. The combined desirability function for the two responses was defined as the geometric mean (7)

$$D = \sqrt{d_1 \ldots d_2}. \tag{7}$$

The values of the individual and combined desirability functions based on the experimental results are shown in Table 5.

Table 5

Values of the individual and combined desirability functions based on the experimental results

No.	Y_1, %	Y_2, %	d_1 (Y_1)	D_2 (Y_2)	D
1	82.2	72.5	0.110	0.300	0.182
2	95.9	71.8	0.795	0.272	0.465
3	89.1	73.3	0.455	0.332	0.389
4	88.8	72.5	0.440	0.300	0.363
5	87.6	82.7	0.380	0.708	0.519
6	94.5	88.9	0.725	0.956	0.833
7	82.8	74.2	0.140	0.368	0.227
8	88.9	83.3	0.445	0.732	0.571
9	85.1	81.8	0.255	0.672	0.414
10	83.9	79.8	0.195	0.592	0.340
11	74.5	76.5	0.000	0.460	0.000
12	95.7	75.7	0.785	0.428	0.580
13	86.3	81.9	0.315	0.676	0.461
14	84.8	78.5	0.240	0.540	0.360
15	90.5	80.2	0.525	0.608	0.565
16	90.4	80.4	0.520	0.616	0.566
17	90.1	80.6	0.505	0.624	0.561
18	90.7	80.8	0.535	0.632	0.581
19	90.8	79.6	0.540	0.584	0.562
20	90.9	80.5	0.545	0.620	0.581

According to the calculation results, the maximum combined desirability was obtained in Experiment No. 6: $Y_1 = 94.5\%$, $Y_2 = 88.9\%$, $D = 0.833$. This regime corresponds to an angular velocity of $\omega = 2.09$ rad/s, a nut rotational speed of $\nu = 1.00$ rpm, and a roughness pitch of $s = 10.0$ mm.

To assess the overall quality of the experimental series, the geometric mean was calculated for all experiments with $D > 0$: $D_{total} = 0.454$.

The graph of the individual and combined desirability functions for the experiments is shown in Fig. 9, 10. The graph of the combined desirability function D for the experiments is shown.

Using the desirability function to simultaneously consider the completeness of shell destruction and the integrity of the kernel. According to the combined function D, experiment No. 6 is the most rational and experimentally confirmed mode, as it ensures a high degree of shell destruction with the highest whole kernel yield among the studied modes. Therefore, this mode can be adopted as the recommended one for further testing and refinement of the setup parameters.

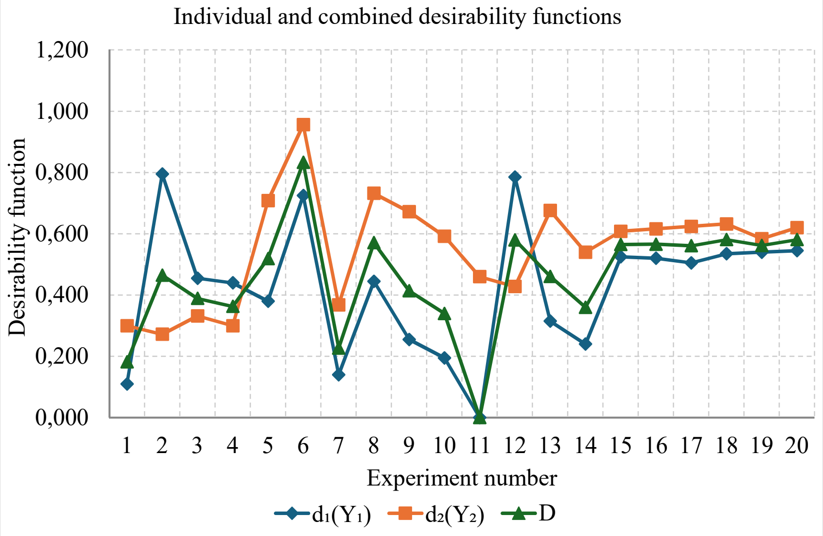


Fig. 9. Graph of individual and combined desirability functions based on experiments

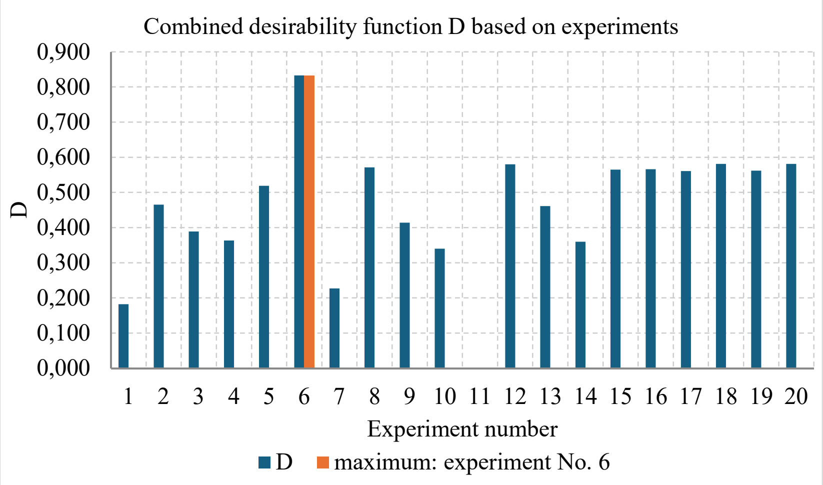


Fig. 10. Graph of the combined desirability function *D* for the experiments

6. Discussion of the walnut shelling process study results

The obtained results show that the walnut shelling process in a setup with a reciprocating millstone is determined by the combined influence of the kinematic parameters of the working elements and the geometry of the contacting surfaces. Moreover, two key process parameters – the degree of shell destruction Y_1 and the whole kernel yield Y_2 – change unevenly. This confirms the existence of a technological compromise: modes that promote more complete shell destruction do not always ensure maximum kernel integrity. An analysis of the regression model for the degree of shell fracture Y_1 shows that the number of revolutions of the walnut in the working channel x_2 has the most pronounced positive effect. Increasing this parameter increases the duration and path of interaction between the walnut and the rough working surfaces, thereby increasing the likelihood of complete shell fracture. This is physically understandable: with a higher number of revolutions, the nut is subjected to a longer period of combined compression, shear, and torsion, which facilitates the propagation of cracks across the shell.

The roughness pitch x_3 has an inverse effect on the degree of shell fracture. Increasing the distance between roughness elements reduces the density of local stress concentrators, resulting in less intense shell fracture. A smaller roughness pitch, conversely, creates more contact zones where local stresses arise sufficient to initiate cracks. However, excessively reducing the pitch can increase the risk of load transfer to the kernel, so this factor should be considered not only from the standpoint of shell breakage but also from the standpoint of kernel integrity.

According to current data, the effect of the angular velocity of the moving upper millstone x_1 on the degree of shell breakage is weaker than the effect of the nut's rotational speed. This means that for the Y_1 indicator, not only the intensity of the impact but also the duration of the nut's contact with the working surfaces is decisive. Consequently, simply increasing the angular velocity is not sufficient to improve the efficiency of shell breakage.

For the whole kernel yield Y_2, a different pattern is observed. The most pronounced negative impact is exerted by the angular velocity of the moving upper millstone. With increasing angular velocity, the intensity of the mechanical impact on the nut increases, increasing the likelihood of kernel damage after shell breakage. Therefore, higher angular velocity can contribute to the intensification of the process, but simultaneously reduces the quality of the final product due to an increased proportion of damaged kernels.

The quadratic effect of the nut's rotational speed x_2^2 on the yield of a whole kernel indicates the existence of a rational range for this parameter. At low rotational speeds, the shell may not be completely broken, which impairs subsequent kernel separation. At excessive rotational speeds, the already cracked nut continues to be subject to mechanical stress, increasing the likelihood of kernel damage. Therefore, the rotational speed should ensure sufficient shell breakage without causing excessive reloading of the kernel.

The advantage of the resulting regression models (3) and (4) is that they describe not a single shell breakage event, but the process result of a machine with a reciprocating millstone. Unlike studies that consider only the strength characteristics of the shell or the impact fracture of the nut, the proposed models link the controlled machine parameters to two practically significant responses: the degree of shell breakage and the yield of a whole kernel.

Compared to conventional impact, centrifugal, or extrusion cracking devices, the system in question utilizes a combination of compression, shear, and torsion. This allows for shell breakage not through a sharp increase in impact energy, but through controlled contact of the nut with rough working surfaces. This approach reduces the risk of excessive kernel damage and allows for the selection of a compromise operating mode.

An additional advantage is the use of a dual-response approach. Process optimization is achieved not only by the degree of shell breakage but also by the yield of intact kernels. This is important, as maximum shell breakage alone does not guarantee high quality of the finished product. Using a combined desirability function (Fig. 9, 10) allows for both criteria to be considered simultaneously, allowing for the selection of a mode that ensures a balance between completeness of cracking and kernel integrity.

The response surfaces shown in Fig. 3–8 clearly demonstrate the varying influence of these factors on the shelling performance. For shell destruction, the most favorable conditions are those that ensure sufficient path for the nut to interact with the working surfaces and generate localized stresses in the shell. For whole kernel yield, more gentle conditions are preferable, where the intensity of the impact is limited and contact stresses do not cause excessive damage to the kernel. Thus, the graphical dependencies demonstrate that the optimal condition cannot be selected based on a single indicator.

To jointly evaluate the two responses, a desirability function (7) was used, which simultaneously takes into account the degree of shell destruction and the yield of whole kernels. This approach allows to move from a separate analysis of Y_1 and Y_2 to the selection of a compromise operating mode for the plant. According to the calculation results, the maximum combined desirability was obtained in Experiment No. 6 (Fig. 10), where the degree of shell destruction was $Y_1 = 94.5\%$, the yield of whole kernels was $Y_2 = 88.9\%$, and the combined desirability function was $D = 0.833$.

Experiment No. 6 (Table 5) corresponds to an angular velocity of the moving upper millstone of $\omega = 2.09$ rad/s, a walnut rotation rate of $\nu = 1.00$ rpm, and a roughness pitch of $s = 10.0$ mm. This mode can be considered a rational, experimentally confirmed mode, as it ensures a high degree of shell destruction with the highest whole kernel yield among the tested options. This is particularly important, as the practical efficiency of the unit is determined not only by the completeness of shell destruction but also by the preservation of the marketable portion of the product.

The obtained result demonstrates that for walnut shelling in a reciprocating millstone setup, it is rational to use a mode with moderate angular velocity, a sufficient number of nut revolutions, and a relatively small roughness pitch. This combination of factors ensures the necessary shell destruction through localized contact action, but does not result in excessive damage to the kernel. This confirms the initial hypothesis that process efficiency is determined by the combined effect of kinematic parameters and the geometry of the working surfaces.

It should be noted that the resulting regression models (3) and (4) are primarily useful for analyzing the directions of influence of factors and constructing response surfaces within the studied region. The final selection of a rational mode was based on the experimental values of the desirability function (Table 5), which increases the practical reliability of the decision. To further refine the setup parameters, it is recommended to conduct additional repeat experiments in the range of mode No. 6, as well as to test the influence of moisture content, nut size group, and shell thickness on the shelling performance. Thus, the study results demonstrate that using a reciprocating millstone with adjustable angular velocity, a specified number of nut revolutions in the working channel, and a variable roughness pitch enables a compromise between complete shell destruction and kernel integrity. The practical outcome of this study is the identification of a rational mode that can be used for further testing, design refinement, and the development of operating recommendations for the walnut shelling system.

The results demonstrate that the shelling performance of a walnut shelling system with a reciprocating millstone is determined jointly by the millstone kinematics and the geometry of the working surfaces, and that these two parameters respond to operating factors in opposite ways. This is evident from regression models (3), (4) and from the response surfaces in Fig. 3–5. Shell destruction increases with increasing angular velocity and number of revolutions and decreases with increasing roughness pitch, while the yield of intact kernels decreases with increasing angular velocity and exhibits internal maxima for both the number of revolutions and the roughness pitch. The explanation for this behavior stems from the process mechanics described in a previous study [21]. Increasing the angular velocity intensifies the combined compression-shear-torsion loading and raises the contact stress above the characteristic shell strength for a larger proportion of the batch, which increases the degree of shell failure. However, this same intensification transfers a greater proportion of the load to the kernel, the strength of which is several times lower than that of the shell, and therefore reduces the yield of intact kernels. The novelty of the obtained result lies in the fact that this conflict is quantitatively assessed for combined compression-shear-torsion loading in a reciprocating millstone and resolved through a specific compromise operating mode.

Several limitations should be noted that determine the applicability of the obtained results. The study was conducted on locally cultivated walnuts with a fixed raw material moisture content of approximately 12%, a specific size group, and within specified ranges of factors: the angular velocity of the moving upper millstone, the number of nut revolutions in the working channel, and the roughness pitch of the working surfaces. Therefore, the obtained regression relationships and the selected rational mode should be considered applicable primarily to the specified experimental conditions. With changes in moisture content, variety, shell thickness, equivalent nut diameter, or kernel condition, the nature of shell failure and the yield of whole kernels may change. Furthermore, the results were obtained on an experimental setup and characterize the process under laboratory conditions; therefore, when transferring to an industrial machine, additional verification of the stability of the selected mode will be necessary.

A limitation of this study is that only three operating parameters of the setup were considered as variable factors. The influence of moisture content, size group, shell thickness, gap between working surfaces, feed rate, and shell aspiration parameters was not specifically studied in this study. Furthermore, shelling parameters were determined after processing a batch of nuts based on product sorting into fractions, without direct measurement of contact forces, torque, and load distribution between the shell and kernel in the working channel. These shortcomings can be addressed further by expanding the experimental design, increasing the number of replicated experiments, using force and torque sensors, high-speed video recording of the destruction process, and more detailed consideration of the initial properties of the raw material.

The main challenges for further study are related to the high natural variability of walnuts as a biological material. Even with the same moisture content and size, nuts can vary in shell thickness, strength, shape, position of the natural cleft, and kernel condition. This complicates obtaining reproducible results and requires a larger sample size. Methodological difficulties may arise when incorporating new factors into the experimental design, as increasing the number of factors dramatically increases the number of necessary experiments. Experimental difficulties arise from the need to record contact forces within a closed working channel and to ensure stable orientation of the nut as it moves between the millstones. Despite these limitations, the obtained results provide a basis for further refinement of the design and operating modes of the reciprocating millstone unit.

7. Conclusions

1. A regression model of the degree of shell destruction Y_1 was obtained, describing the influence of the angular velocity of the moving upper millstone, the number of walnut revolutions in the working channel, and the roughness pitch of the working surfaces. Analysis of the model revealed that the number of nut revolutions in the working channel has the most pronounced positive effect on the degree of shell destruction. Increasing this factor increases the duration of contact between the nut and the working surfaces and promotes more complete shell destruction.
2. It was found that the yield of whole kernels Y_2 is most sensitive to the angular velocity of the moving upper millstone. Increasing the angular velocity reduces the yield of whole kernels, as the intensity of mechanical impact increases and the likelihood of damage to the kernel after shell destruction increases. A quadratic effect was found for the number of nut revolutions, indicating the presence of a rational region: an insufficient number of revolutions does not ensure complete shell destruction, while an excessive number of revolutions leads to repeated loading of the already cracked nut and a decrease in the preservation of the kernel.
3. A combined desirability function was used to jointly evaluate the two parameters. The maximum desirability function value was obtained in Experiment No. 6: the shell fracture rate was $Y_1 = 94.5\%$, the whole kernel yield was $Y_2 = 88.9\%$, and the combined desirability function was $D = 0.833$. This regime corresponds to an angular velocity of the moving upper millstone of $\boldsymbol{\omega} = 2.09$ rad/s, a nut rotation rate in the working channel of $\boldsymbol{\nu} = 1.00$ rpm, and a roughness pitch of the working surfaces of $s = 10.0$ mm.

Conflict of interest

The authors declare that they have no conflicts of interest with respect to this study, whether financial, personal, authorial, or otherwise, that could influence the study and its results presented in this article.

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The study was conducted without financial support.

Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies in creating this work.

Authors contributions

Temov Baurzhan: Investigation, Data curation, Data processing; **Nurakhmetov Baurzhan**: Supervision; **Askarov Ardak**: Conceptualization, Methodology, Writing – review & editing; **Nurakhmetov Ilyas**: Formal analysis, Data analysis, Statistics; **Nasrullin Galymzhan**: Formal analysis, Data analysis, Statistics.

References

1. Bao, X., Chen, B., Dai, P., Li, Y., Mao, J. (2022). Construction and Verification of Spherical Thin Shell Model for Revealing Walnut Shell Crack Initiation and Expansion Mechanism. Agriculture, 12 (9), 1446. https://doi.org/10.3390/agriculture12091446
2. Zhang, H., Shen, L., Lan, H., Li, Y., Liu, Y., Tang, Y., Li, W. (2018). Mechanical properties and finite element analysis of walnut under different cracking parts. International Journal of Agricultural and Biological Engineering, 11 (6), 81–88. https://doi.org/10.25165/j.ijabe.20181106.3309
3. Koyuncu, M. A., Ekinci, K., Savran, E. (2004). Cracking Characteristics of Walnut. Biosystems Engineering, 87 (3), 305–311. https://doi.org/10.1016/j.biosystemseng.2003.11.001
4. Altuntas, E., Erkol, M. (2009). The Effects of Moisture Content, Compression Speeds, and Axes on Mechanical Properties of Walnut Cultivars. Food and Bioprocess Technology, 4 (7), 1288–1295. https://doi.org/10.1007/s11947-009-0283-y
5. Shahbazi, F. (2013). Effective conditions for extracting higher quality kernels from walnuts. Quality Assurance and Safety of Crops & Foods, 5 (3), 199–206. https://doi.org/10.3920/qas2011.0105
6. Han, B., Su, G., Zeng, Y., Yang, J., Fan, X., Zhang, Y. et al. (2023). FDEM investigation on the crack propagation characteristics of walnut shell under multi-contact loadings. Frontiers in Materials, 10. https://doi.org/10.3389/fmats.2023.1293683
7. Zhang, H., Liu, H., Zeng, Y., Tang, Y., Zhang, Z., Che, J. (2022). Design and Performance Evaluation of a Multi-Point Extrusion Walnut Cracking Device. Agriculture, 12 (9), 1494. https://doi.org/10.3390/agriculture12091494
8. Chengmao, C., Si, S., Ran, D., Bing, L., Shuo, W. (2017). Experimental study on mechanical characteristics of nut rupturing under impact loading. International Journal of Agricultural and Biological Engineering, 10 (1), 53–60. https://doi.org/10.3965/j.ijabe.20171001.2331
9. Karimi, N., Minaei, S., Hasani, D., Eyvani, A. (2008). Parameters Involved in Walnut Peeling Process. Journal of Agricultural Machinery Science, 4 (4), 389–393. Available at: https://dergipark.org.tr/en/download/article-file/119118
10. Altuntas, E., Özkan, Y. (2008). Physical and Mechanical Properties of Some Walnut (Juglans regia L.) Cultivars. International Journal of Food Engineering, 4 (4). https://doi.org/10.2202/1556-3758.1349
11. Aviara, N. A., Ajikashile, J. O., Lawal, A. A. (2012). Effect of moisture content and impact energy on the cracking of conophor nut. Agricultural Engineering International: CIGR Journal, 14 (2), 68–76. Available at: https://cigrjournal.org/index.php/Ejounral/article/view/2008
12. Ojolo, S. J., Damisa, O., Orisaleye, J. I., Ogbonnaya, C. (2010). Design and development of cashew nut shelling machine. Journal of Engineering, Design and Technology, 8 (2), 146–157. https://doi.org/10.1108/17260531011062528
13. Olaoye, J. O., Adekanye, T. A. (2018). Properties influencing cracking and separation of palm nuts in a mechanical cracker cum separator. Croatian Journal of Food Science and Technology, 10 (1), 42–50. https://doi.org/10.17508/cjfst.2018.10.1.07
14. Opobiyi, A. T., Ishola, T. A., Ariyo, E. O., Abioye, K. J. (2019). Development of a Walnut (Tetracarpidium conophorum) Cracker. KMUTNB International Journal of Applied Science and Technology, 12 (1). https://doi.org/10.14416/j.ijast.2019.01.003
15. Iyilade, I. J., Aviara, N. A., Oyeniyi, S. K., Aremu, A. K. (2019). Performance Evaluation of a Bush Mango (Irvingia gabonensis) Nut Cracking Machine. Agricultural Engineering International: CIGR Journal, 21 (1), 156–162. Available at: https://cigrjournal.org/index.php/Ejounral/article/download/5093/2923/22955
16. Ibiyeye, D., Olunloyo, O., Aderemi, A., Emmanuel, I.-O., Akala, A., Owolola, O. (2022). Design and development of a palm kernel nut cracking unit. Technology Audit and Production Reserves, 1 (3 (63)), 30–44. https://doi.org/10.15587/2706-5448.2022.253931
17. Sam, E. O., Ndirika, V. I. O., Umoh, A. T., Usoh, G. A., Umoh, E. O. (2024). Determination of the Optimum Moisture Content for the Whole Kernel Recovery During the Cracking Process of Oil Palm Nuts. Advanced Journal of Science, Technology and Engineering, 4 (4), 125–138. https://doi.org/10.52589/ajste-cwcbfgjp
18. Maghsoudi, H., Khoshtaghaza, M. H., Minaei, S., Zaki Dizaji, H. (2012). Fracture Resistance of Unsplit Pistachio (Pistacia vera L.) Nuts against Splitting Force, under Compressive Loading. Journal of Agricultural Science and Technology, 14, 299–310. Available at: https://www.cabidigitallibrary.org/doi/pdf/10.5555/20123079723
19. Valentini, N., Rolle, L., Stévigny, C., Zeppa, G. (2006). Mechanical behaviour of hazelnuts used for table consumption under compression loading. Journal of the Science of Food and Agriculture, 86 (8), 1257–1262. https://doi.org/10.1002/jsfa.2486
20. Temov, B. M., Shalbaev, K. K., Askarov, A. D. (2022). Pat. No. 10179 RK. Ustanovka dlya ochistki greckih orehov ot skorlupy.
21. Temov, B., Nurakhmetov, B., Askarov, A., Nurakhmetov, I., Nasrullin, G. (2026). Identifying patterns of walnut shell fracture under combined loading in a reciprocating millstone system. Eastern-European Journal of Enterprise Technologies, 2 (11 (140)), 6–18. https://doi.org/10.15587/1729-4061.2026.358671