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DEVELOPING AN EFFICIENT AND ECONOMICALLY VIABLE METHOD FOR PINE NUT PROCESSING

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This study examines the strength characteristics of pine nut shells to enhance kernel extraction efficiency. Current methods have drawbacks, including high kernel damage, preheating, and excessive energy use. Laboratory tests using the ST-2 structural meter analyzed the shell's mechanical and rheological properties under varying moisture conditions.

The most effective shell-breaking method without kernel damage (for nuts 10.8–11.4 mm in diameter) involves a 90° cone indenter at a shell moisture level of 16–17%, with an average breaking force of 7.0 kg. Mathematical modeling determined that under an impact force of 49 N and deformation of 1.1–1.3 mm, the required fracture energy is 0.245 J. Finite element analysis in Inventor software confirmed a pre-fracture displacement of 0.016 mm, with stress uniformly distributed across the shell.

A pendulum-based test rig studied shell fracture under impact loads. The optimal cracking mode was achieved with an impact mass of 40–60 g at a velocity of 35–40 m/s. A grooved impact surface (90°) with an L/D ratio of 0.4–0.6 reduced fracture energy by 10–15%.

Pre-acceleration in an air stream before impact caused the least kernel damage, but low aerodynamic resistance limited efficiency. To address this, a new device was developed, combining a rotating toothed disk for initial acceleration with a compressed air stream to achieve an optimal velocity of 35–40 m/s. This approach increased whole kernel yield by 15–20%, reduced energy consumption by 10%, and minimized product damage.

The proposed method improves pine nut processing by increasing efficiency, reducing waste, and lowering costs. It is applicable in food and pharmaceutical industries for optimized kernel extraction while preserving product integrity

Keywords: pine nut, shell, efficient device, rheological and mechanical properties, strength calculation

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1. Introduction

The pine nut industry plays a crucial role in the global market, with increasing demand due to the nut's high nutritional and pharmaceutical value. Republic of Kazakhstan, particularly the Eastern region, is home to pine nut varieties comparable to those found in the Russian Far East, yet the country lacks industrial-scale processing facilities. As a result, most raw nuts are exported to neighboring countries for processing, leading to economic inefficiencies and lost opportunities for domestic value-added production.

One of the major challenges in pine nut processing is the effective and efficient extraction of kernels while minimizing damage and energy consumption. Conventional methods, including mechanical crushing, thermal treatment, and pneumatic acceleration, exhibit significant drawbacks. Mechanical crushing often leads to kernel breakage and contamination, reducing the quality and market value of the final product. Thermal treatment, though effective in softening the shell, can compromise the nutritional properties of the nut. Pneumatic acceleration, while less damaging, is highly dependent on precise control of impact parameters and is often limited by the aerodynamic properties of the nuts.

The technological development of energy-efficient and low-damage shell-breaking equipment is of significant importance for both industrial and small-scale producers. As pine nut production expands, sustainable processing methods are required to reduce waste, optimize energy use, and improve product quality. Research in material strength, impact mechanics, and fracture behavior is fundamental to, advancing this field and developing innovative processing solutions.

Furthermore, the increasing focus on sustainability in the food industry demands more eco-friendly processing technologies. Traditional processing methods contribute to excessive waste and high energy consumption, contradicting modern principles of sustainable production. Therefore, developing advanced, efficient, and environmentally friendly pine nut shell-breaking technologies aligns with global trends toward sustainability and resource optimization.

Given these factors, further research into the mechanical properties of pine nut shells and the optimization of processing technologies is essential. Advancing scientific understanding in this area will contribute to the development of improved industrial methods, benefiting both economic and environmental aspects of the pine nut processing industry.

Therefore, research devoted to the improvement of pine nut processing technologies, particularly the development of efficient and sustainable shell-breaking methods, remains highly relevant.

2. Literature review and problem statement

Recent research on nut shell fracture mechanisms has expanded significantly, driven by the need for more efficient, scalable, and low-damage kernel extraction technologies. A number of studies have addressed the influence of moisture content on shell strength. For example, in paper [1] demonstrated that pine nut shells become more ductile under elevated moisture levels, leading to a reduction in the force required for fracture. Similarly, paper [2] determined a critical moisture threshold for walnut shell rupture and proposed a drying process for optimizing mechanical properties. However, these studies did not explore the industrial limitations related to moisture regulation, such as energy costs associated with drying and the potential negative impact of overhydration on fracture consistency. Additionally, their applicability to pine nuts – which differ structurally from walnuts and almonds – remains uncertain.

From a modeling perspective, several papers have examined shell fracture through theoretical and numerical methods. In paper [3] applied finite discrete element modeling (FDEM) to simulate multi-point fracture in walnut shells, offering insight into stress propagation. Yet, the variability in shell geometry and thickness, particularly in irregular pine nuts, was not accounted for. Paper [4] introduced the use of salt solutions to soften pine nut shells, reporting improved shell removal rates. However, the proposed method required additional processing stages and was not compared directly with mechanical or pneumatic alternatives, limiting its practical relevance.

Studies on mechanical properties and deformation behavior under compression have also contributed to understanding shell fracture. In paper [5] investigated how moisture, die thickness, and temperature affect walnut shell pellet compaction – a process not directly analogous to shell cracking – thus offering limited insight for kernel-preserving fracture. Papers [6] and [7] provided chemical and mechanical characterizations of pine nut shells, but without proposing practical engineering solutions. Paper [8] analyzed energy thresholds for controlled shell fracture using continuous damage mechanics, highlighting the importance of energy input control but not addressing how such control could be applied in dynamic industrial systems.

Research [9] on aerodynamic and physical properties of pine nuts provided useful data for pneumatic acceleration designs. However, the low drag coefficient of the spherical nut shape complicates acceleration efficiency and was not sufficiently addressed in terms of energy trade-offs. Moreover, existing pneumatic shell-breaking devices often require long pipelines and high airflow volumes, making them energy-intensive and less adaptable to continuous operation.

Although many works investigate nut fracture processes or shell properties, only a limited number directly address the combination of mechanical impact, airflow-assisted acceleration, and real-time control of fracture conditions. Prior works tend to focus on specific variables (e.g., compression force, moisture) in isolation, without integrating theoretical modeling, experimental validation, and prototype device development. In addition, many findings have not been validated under processing conditions typical of industrial environments, nor have they yielded scalable technological solutions.

Given these unresolved issues, it is evident that further research is required to develop a pine nut shell-breaking method that is both energy-efficient and scalable, while preserving the integrity of the kernel. Such a solution must account for the mechanical complexity of the shell structure, moisture-dependence of fracture behavior, and the aerodynamic challenges involved in controlled nut acceleration. Therefore, this study aims to address these gaps by combining theoretical modeling of shell strength, experimental investigation of fracture dynamics, and the design of an innovative two-stage acceleration device. The ultimate goal is to improve kernel yield, reduce energy use, and enable continuous, industrially applicable processing of pine nuts.

3. The aim and objectives of the study

The aim of the study is to develop an efficient and economically viable method for pine nut processing that minimizes kernel damage, reduces energy consumption, and optimizes processing parameters for diverse raw materials.

To achieve this aim, the following objectives are accomplished:

– to conduct a static analysis of cedar nut shell cracking;

– to develop a theoretical model for pine nut shell strength under impact loads;

– to investigate the mechanical properties of pine nut shells under impact loads;

– to design and develop a device for efficient pine nut shell fracture.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of the study is the pine nut shell and its mechanical behavior under various loading conditions, with the aim of developing an effective method for kernel extraction that minimizes damage and energy consumption.

The main hypothesis of the study is that pine nut shells, when subjected to controlled mechanical and aerodynamic acceleration followed by impact with a properly designed striking surface, can be fractured efficiently without compromising kernel integrity. It is assumed that optimizing the impact parameters, such as nut moisture content, velocity, and surface roughness of the impact zone, will significantly reduce fracture energy and improve processing efficiency.

Assumptions made in the study include the following:

– the pine nut shell behaves as a brittle or viscoelastic material depending on its moisture content;

– the kernel has higher plasticity than the shell and deforms under load before cracking;

– the air-nut mixture achieves uniform velocity distribution after flow stabilization;

– the impact occurs predominantly on the side surface of the nut, where shell thickness is consistent.

Simplifications adopted in the study are:

– the shell is modeled as a thin-walled spherical shell with uniform thickness;

– material properties such as elasticity, strength, and density are considered homogeneous for modeling purposes,

– the aerodynamic drag is treated as a constant within the effective velocity range;

– frictional losses and turbulence in the air-nut stream are neglected in theoretical energy calculations.

4. 2. Investigation of rheological properties of pine nuts on laboratory equipment

The mechanical properties of pine nuts can vary significantly due to multiple factors, including their growing region, size, the ratio of kernel mass to shell mass, shell thickness, and moisture content. These variables influence the nut's structural integrity and crocking behavior. For this study, a batch of pine nuts cultivated in the Katon-Karagay region (Republic of Kazakhstan) was selected and conditioned to a specific moisture level to ensure consistency in testing.

To analyze their rheological properties, experiments were conducted using a ST-2 structural meter (Fig. 1). Key parameters examined included nut geometry, mass, moisture content, the type of indenter used for shell cracking, and the velocity at which the indenter moved.

The ST-2 structural meter is specifically designed to measure the mechanical properties of materials under different loading conditions [10]. In this study, it was used to evaluate the shell's resistance to various types of indenters, providing insight into its strength characteristics based on load direction and concentration.

In this study, the following indenters were employed (Fig. 2):

– Tarr-Baker indenter – characterized by a flat working surface, ensuring uniform load distribution across the nut. This indenter was used to measure the overall shell strength;

– 45° cone indenter – features a conical shape with a sharp inclination angle. This indenter allowed for localized impact on a specific shell section, enabling the assessment of its resistance to cracking under concentrated load;

– 90° cone indenter – distinguished by a conical shape with a blunt angle. Its application was aimed at simulating loading conditions most similar to natural mechanical impacts.

Fig. 1. Measuring device: structural meter ST-2

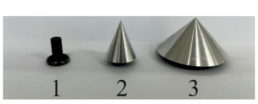


Fig. 2. Indenters used in the study: 1 — Tarr-Baker indenter; 2 — 45° cone indenter; 3 — 90° cone indenter

These experiments will provide valuable data on the mechanical behavior of pine nut shells under various loads. The obtained results will help optimize shell-breaking technologies, ensuring more efficient pine nut processing.

4. 3. Influence of moisture on the strength properties of the shell

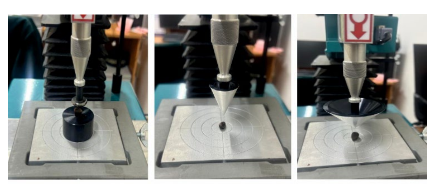
Moisture content significantly affects the mechanical properties of the pine nut shell. Under high humidity conditions, the shell becomes more plastic and capable of withstanding higher loads without fracturing. Conversely, at low moisture levels, the shell becomes brittle, harder, and more resistant to controlled destruction.

During the experiment, a batch of nuts was treated with regular steam, and for strength property analysis, samples were selected with moisture levels of 16.4%, 15.7%, and 9.2%. The primary criterion during the experiments was minimizing kernel damage.

The nut mass was measured using Vibra ALE-6202R scales (Fig. 3), while their moisture content was determined using a Wile 55 moisture meter (Fig. 4). Fig. 5 illustrates the testing process of pine nuts using the ST-2 structural meter, where different indenters are applied.

Fig. 3. Measurement of nut mass using Vibra ALE-6202R scales

Fig. 4. Measurement of nut moisture using Wile 55 moisture meter



1 2 3

Fig. 5. Testing of nuts using the ST-2 structural meter: 1 — Tarr-Baker indenter; 2 — 45° cone indenter; 3 — 90° cone indenter

The results demonstrated that increasing moisture content reduced the force required to fracture the shell while lowering the risk of kernel damage. These findings highlight the importance of moisture control in optimizing pine nut processing efficiency.

5. Results of research on pine nut shell fracture efficiency

5. 1. The static analysis of pine nut shell cracking

The tests were conducted using three types of indenters: Tarr-Baker, 45° cone, and 90° cone (Fig. 5). The ST-2 structural meter was configured to ensure the shell cracked without damaging the kernel.

The experiment followed a three-stage process:

– Stage 1: the indenters moved downward at a velocity of $V_m = -0.5$ mm/s until they made contact with the nut with a force of $F_k = 10$ g;

– Stage 2: the indenters applied a force of up to $F_{max} = 12{,}000$ g at a loading velocity of $V_n = 10$ g/s, continuing until the shell fractured;

– Stage 3: after the fracture, the indenters moved upward at a velocity of $V_m = 3$ mm/s.

Each indenter underwent 10 test trials under different moisture levels and nut geometries. Due to their extensive size, the full test results are not included in this paper. However, statistical analysis was conducted using Statistica 10 software, and the processed results are presented graphically in Fig. 6–8.

The data presented in Fig. 6 indicate that the forces applied to the nut can reach up to 18 kg. The lowest forces were recorded at a moisture content of 15–16% when the nut size ranged from 11 to 12 mm. However, it is important to note that kernel deformation was also observed under these conditions, which is undesirable for effective processing.

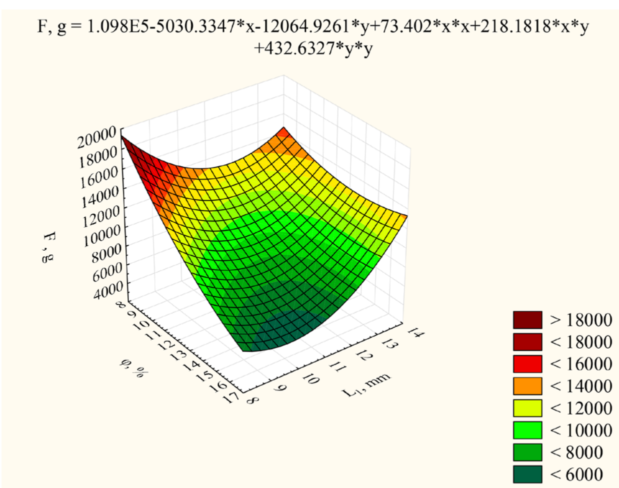


Fig. 6. Graph of the interdependence of force F, shell moisture φ and nut length L_1 (Tarr-Baker indenter)

The data in Fig. 7 show that the applied force on the nut reaches its lowest level, up to 2.5 kg. At a moisture content of 11–12%, the applied force drops to 0 kg, indicating that the shell fractures completely. Under these conditions, kernel deformation does not occur, but the kernel itself is punctured. Additionally, at a moisture content of 17%, the indenter penetrates the nut with ease, damaging both the shell and the kernel.

The data presented in Fig. 8 indicate that the applied forces on the nut are moderate, reaching up to 7 kg. The lowest forces were observed at a moisture content of 16–17% and a nut size of 10.8–11.4 mm. This graph provides a basis for selecting an optimal force value under specific moisture conditions, ensuring that shell deformation leads to fracture without unnecessary kernel damage.

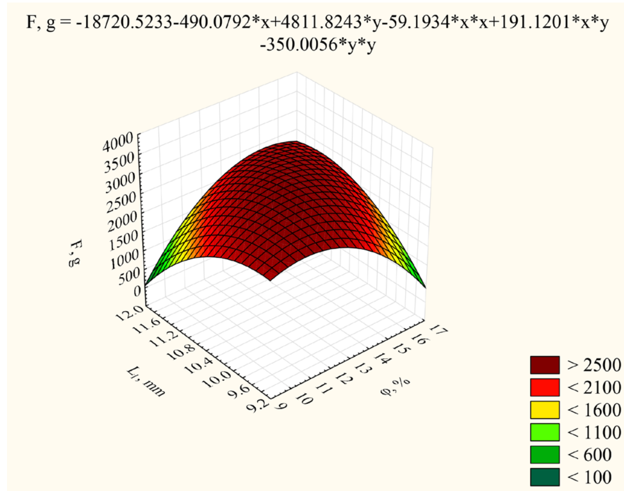


Fig. 7. Graph of the interdependence of force F, shell moisture φ and nut length L_1 (45° cone indenter)

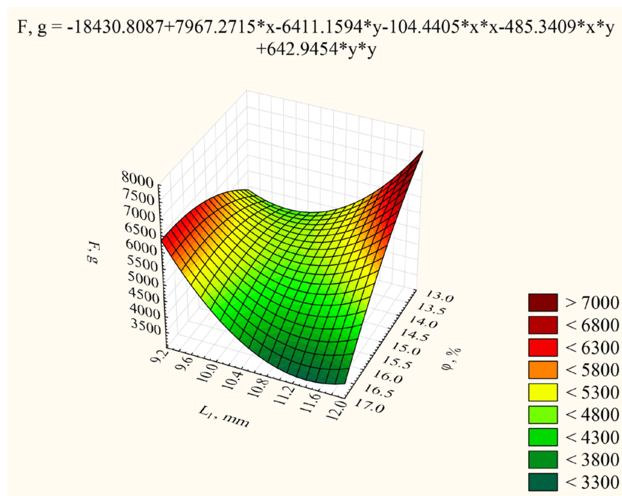


Fig. 8. Graph of the interdependence of force F, shell moisture φ and nut length L_1 (90° cone indenter)

Based on the experimental results, the following optimal parameters were identified for achieving energy-efficient and gentle shell cracking:

1. The ideal moisture content for the nuts is 15–16%.
2. The 90° cone indenter proved to be the most effective. Although sharper indenters reduce the required force, they tend to puncture the kernel, which is undesirable.

These tests also enabled the calculation of fracture energy as the average product of force and deformation. The data revealed that, regardless of the indenter type, the shell fractures at a deformation of 1.1–1.3 mm (Fig. 9).

For instance, with the 90° cone indenter, the average fracture force was 5 kg (49 N), leading to a fracture energy of $49 \times 5 = 0.245$ J.

In future studies, these values will serve as reference parameters for designing a testing rig to evaluate shell strength. The results of comparative tests conducted on a batch of nuts using the structural meter are presented in Fig. 9, showing averaged data obtained at uniform moisture levels.

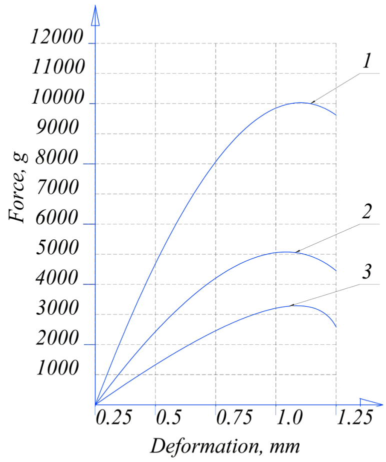


Fig. 9. Comparative data on shell fracture at uniform moisture levels: 1 – Tarr-Baker indenter; 2 – 90° cone indenter; 3 – 45° cone indenter

These findings will help refine experimental methodologies and improve the accuracy of shell strength assessments. Additionally, they will contribute to the development of optimized cracking techniques that minimize kernel damage while enhancing processing efficiency.

5. 2. Theory of pine nut shell strength calculation under impact loads

To determine the strength of a pine nut shell, it is essential to consider its elastic-plastic properties while also analyzing its behavior as a brittle material prone to cracking and fracturing.

Understanding the shell's fracture process under impact forces requires analyzing how impact loads affect its structure. This approach allows to describe the shell's behavior under stress and apply fracture mechanics principles.

The kinetic energy transferred by a falling weight to the shell-leading to its deformation and eventual destruction – is expressed as

$$W_{kin} = \frac{m_n \cdot V_n^2}{2}, \tag{1}$$

where, m_n – nut mass (kg); V_n – impact velocity of the nut against a solid surface.

Similarly, this energy can also be defined in terms of the mass and velocity of the striking weight

$$W_{kin} = \frac{m_n \cdot V_n^2}{2} = \left(m_w \cdot V_w^2\right) \div 2, \tag{2}$$

where m_w – mass of the striking weight (kg); V_w – velocity of the striking weight at the moment of impact.

The impulse force, which measures the change in momentum during impact, is given by

$$I = F \cdot \Delta t, \tag{3}$$

where F – impact force (N); Δt – impact duration (s).

Previous experiments indicate that shell fracture occurs when the indenter penetrates to a depth of Δh. This penetration depth allows to estimate the contact time between the weight and the shell

$$\Delta t = \Delta h / V_n. \tag{4}$$

From this, the impact force exerted on the nut shell can be determined as

$$F = \frac{I}{\Delta t}. \tag{5}$$

The stiffness of the shell plays a crucial role in determining the energy required for fracture, as the shell possesses finite strength before breaking. By understanding these mechanical properties, it is possible to optimize shell-cracking techniques to balance efficiency and minimal kernel damage.

When an impact occurs, energy is transferred to the shell, generating internal stresses. If this energy surpasses the shell's compressive strength limit, the shell will crack or fracture. In this case, the impact force is concentrated at specific points, influencing stress localization.

Previous studies suggest that at low moisture levels, the pine nut shell behaves as a brittle material, fracturing upon reaching its ultimate stress limit with minimal plastic deformation. However, as moisture content increases, the shell exhibits viscoelastic-plastic properties, altering its fracture behavior.

The critical stress (σ_{kr}) represents the maximum stress the shell can withstand before failure. The degree of shell deformation depends on its elastic modulus (E) and is calculated using the formula

$$\sigma_{cr} = \frac{F}{A}, \tag{6}$$

where F – applied force (N); A – contact area (mm^2).

For localized fracture analysis, calculating the force and contact area is essential in determining the conditions under which the shell will fail. If the applied force exceeds the critical stress, the shell will crack.

In our opinion, the fracture process can be divided into three distinct stages. The first stage is initial deformation under an applied force, the shell experiences slight elastic deformation. The second stage of destruction is crack formation and propagation, if the stress surpasses the shell's strength limit, cracks begin to form. Due to the brittle nature of the material, these cracks can spread rapidly. The third stage is complete fracture, when the crack reaches a critical length, the shell fully breaks apart, releasing the kernel.

In this study, the pine nut shell is modeled as a thin-walled spherical shell subjected to an externally applied concentrated force. This approximation allows for an accurate evaluation of the strength characteristics of the shell using structural mechanics principles.

The bending moment (M) generated in the shell due to an applied concentrated force (F) can be calculated using the thin-walled spherical shell equation

$$M = \left(F \cdot R^2\right) \div 2\delta, \tag{7}$$

where M – bending moment (N·mm); F – applied force on the nut shell (N); R – radius of the nut (mm); δ – shell thickness (mm).

In this case, the concentrated force (F) can be precisely simulated using specialized testing equipment, making this parameter known and controlled.

By applying strength calculations for this geometrical model, it becomes possible to predict the critical load at which the shell will fracture. Utilizing thin walled shell equations, it is possible to determine the optimal force and pressure distribution along the shell's surface, ensuring an efficient cracking process while minimizing kernel damage.

Calculation results using previously obtained experimental data. Since the thin-walled spherical shell calculation methodology is well-established in the design of dome-shaped architectural structures, Autodesk Inventor was employed within the finite element method (FEM) system for our analysis. The results were compiled into Table 1 and visualized in Fig. 10 for better interpretation.

Table 1

Test parameters for pine nut shell analysis in inventor software

Material	Pine nut	
Density	0.553 g/cm^3	
Mass	0.000204122 kg	
Surface area	256.37 mm^2	
Volume	369.117 mm^3	
Center of mass	x=0 mm	
	y=−0.0000000309518 mm	
	z=−5.15959 mm	
Design objective	Parametric dimensions	
Type of study	Static analysis	
Detection and elimination of rigid body modes	No	
Average element size (fraction of model diameter)	0.1	
Minimum element size (fraction of average element size)	0.2	
Heterogeneity coefficient	1.5	
Maximum rotation angle	60°	
Creating curved mesh elements	Yes	
Total	Mass density	0.553 g/cm^3
	Yield strength	35 MPa
	Ultimate tensile strength	0 MPa
Stress	Young's modulus	9.8 GPa
	Poisson's ratio	0.0001 br
	Shear modulus	2.89951 GPa
Component names	Pine nut 3.ipt	
Type of load	Force	
Magnitude	50.0 N	

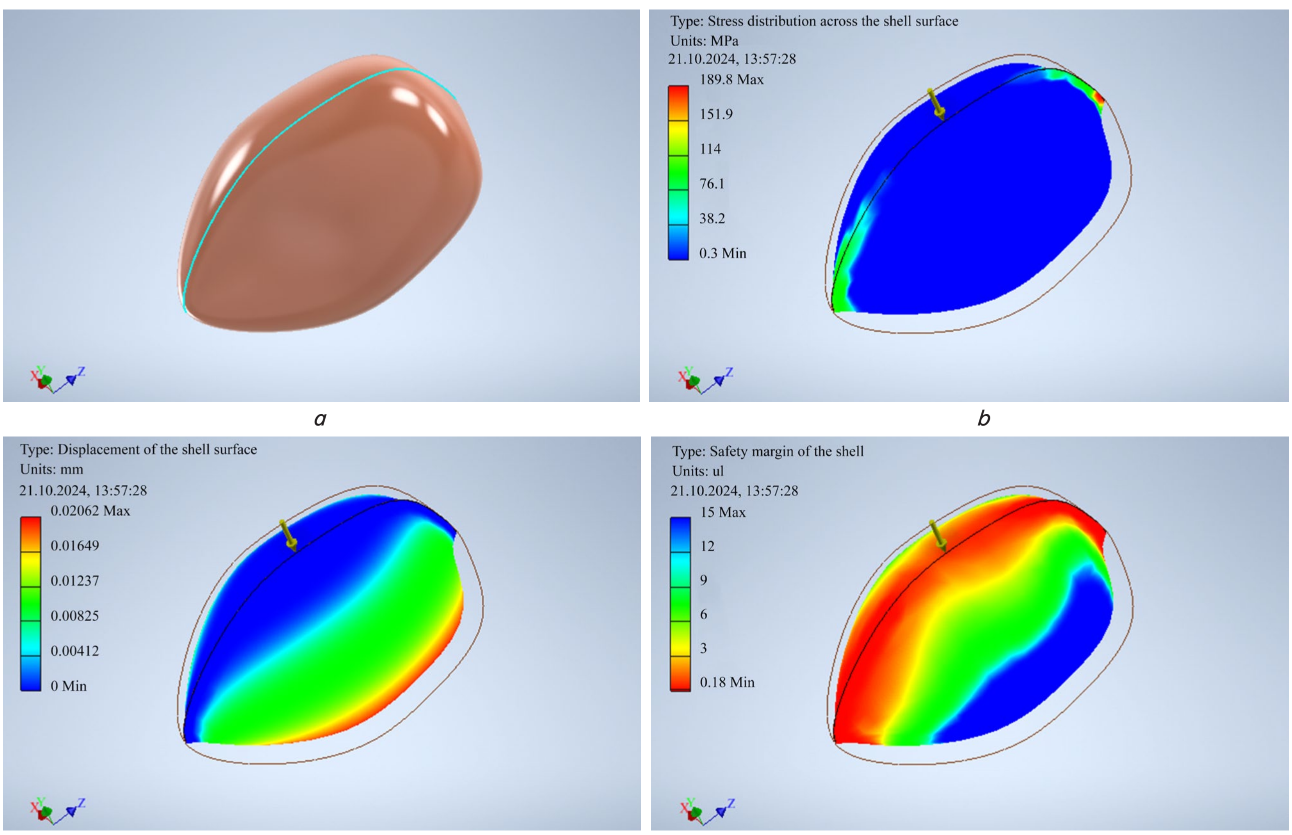


Fig. 10. Results of strength calculations for pine nut shells using Inventor software:
a — overall view of the shell with applied load; *b* — stress distribution across the shell surface;
c — displacement of the shell surface; *d* — safety margin of the shell

The results of the strength calculations for the pine nut shell as a thin-walled spherical shell under a concentrated force load show that the initial stress is primarily distributed evenly across the entire surface of the shell. Only slight increases in stress are observed at the head and tail sections. The displacement of the nut shell before fracture is shown in Fig. 10, *c*. The largest displacement occurs along the side surface of the nut, reaching 0.016 mm. The minimum safety margin of the shell under concentrated load is observed along the central axis of the nut (Fig. 10, *d*).

The strength calculation for this geometry allows to predict the load level at which the shell fractures. By using the formulas (1)–(7) for thin-walled shells, it is possible to calculate the optimal force and pressure distribution along the perimeter of the shell.

5. 3. Investigation of pine nut shell strength under impact loads

To address the challenges of determining the fracture energy of pine nut shells under impact loads and to evaluate the influence of different surface roughness on reducing the fracture energy, it is possible to develop a stand for measuring the impact energy during shell fracture. The stand was designed based on the principles of a pendulum hammer, which is commonly used to determine the resistance of materials to impact loads.

According to the data presented in source [7, 8, 11–13], the optimal fracture velocity of the nut shell in an air stream is between 35–40 m/s. Therefore, when designing the stand, it is possible to incorporate data obtained from testing the rheological properties of the nut shell using the ST-2 structural meter.

To ensure the required fracture energy at an impact velocity of 35–40 m/s, the operational parameters of the stand were based on the following relationship: a mass m_L suspended at a height H possesses potential energy.

The equations describe the relationship between potential energy, kinetic energy, and the variables involved in the impact process.

Potential energy of the dropped load

$$W_{pot} = m_L \cdot g \cdot H, \tag{8}$$

where m_L – mass of the dropped load (kg); g – acceleration due to gravity (9.81 m/s^2); H – height from which the load is dropped (m).

Kinetic energy of the nut shell fracture

$$W_{kin} = \frac{m_n \cdot V_n^2}{2}, \tag{9}$$

where m_n – nut mass (kg); V_n – impact velocity of the nut when it strikes the plate (m/s).

Since the potential energy of the dropped load is converted into kinetic energy that fractures the nut shell, let's equate the two

$$W_{pot} = W_{kin} \text{ or } 2 \cdot m_L \cdot g \cdot H = m_n \cdot V_n^2. \tag{10}$$

This equation demonstrates that the kinetic energy of the nut upon impact is equivalent to the potential energy of the dropped load. By rearranging this, it is possible to solve for the impact velocity V_n or other variables based on the existing parameters.

Based on these relationships, it is possible to assume the mass of the dropped load m_w to be 40–60 g, and the drop height H to be 50–60 cm. Fig. 11 illustrates the schematic of this stand. It consists of a relatively massive base 1, to which a vertical support 2 is attached. A transverse beam 4 is mounted on the support at a height of 50–60 cm. At a distance of 15–20 cm from the beam, an electromagnet 5 is rigidly suspended, powered by a 12-volt battery. A button is used to disconnect the circuit and deactivate the magnet. When the electromagnet is operational, the impact load 6, weighing 40–60 grams, is suspended. The load on the impact side has roughing 7, which features a 90° sharpening angle and various center-to-center distances between the pyramid tips, denoted by 1 (Fig. 12).

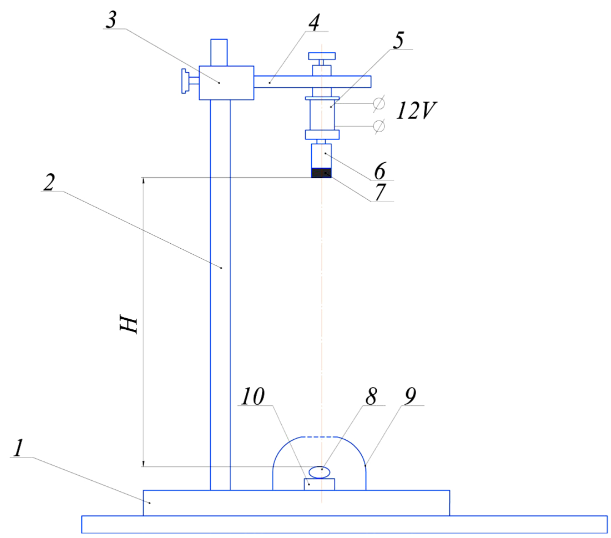


Fig. 11. Scheme of the stand for measuring impact energy during pine nut shell fracture: 1 – base; 2 – vertical support; 3 – adjustable clamping device; 4 – horizontal beam; 5 – electromagnet; 6 – impact load; 7 – roughing of the impact surface; 8 – pine nut; 9 – transparent cover; 10 – anvil

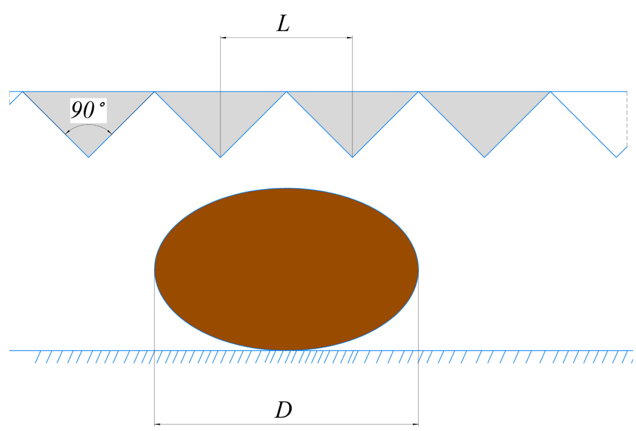


Fig. 12. Scheme of the roughness on the impact surface of the striking plate

In our opinion, this stand allows for accurate calculation of the impact energy required for the shell fracture because, in this case, the potential energy of the suspended load at a given height is easily calculated. When this energy is converted into kinetic energy, it is straightforward to determine the energy with which the nut, accelerated by the impact, strikes the obstacle.

The stand operates as follows: a steel load, with a pre-determined mass, is suspended from the electromagnet 5, which is equipped with a special plastic guide to center the load along the fall axis. Simultaneously, the test nut 8 is placed onto an anvil 10, which has a spherical indentation in the center. The fall height of the load is measured using a caliper ruler. The nut and anvil are enclosed with a transparent cover 9, which has a central hole. After that, the electromagnet is disconnected from the network, causing the impact load to fall and strike the nut precisely at the center.

Study of the roughness effect on the impact resistance to cracking. The type of surface against which the mass, accelerated to a certain velocity, impacts is of significant importance. The reason for this is that during the impact with a roughened surface, a significant reduction in the area of initial contact between the nut shell and the obstacle occurs. This reduction in contact area leads to easier cracking of the nut shell. Therefore, the dimensions of the roughening on the impact plate, in particular, the sharpness angle ratio of the pyramid tips, as well as the distances between their centers, require an investigation for optimizing the shape of the roughened surface to minimize the cracking resistance of the shell.

During the strength testing of the pine nut shell it was found that the optimal value, at which a gentle cracking mode is observed, is the ratio between the centers of the pyramid tips and the large diameter of the nut $L/D = 0.4–0.6$ (Fig. 13).

As an example, Table 2 presents the data for determining the strength of the pine nut shell under impact loads. The results were processed using the "Statistics" software and are shown in Fig. 14.

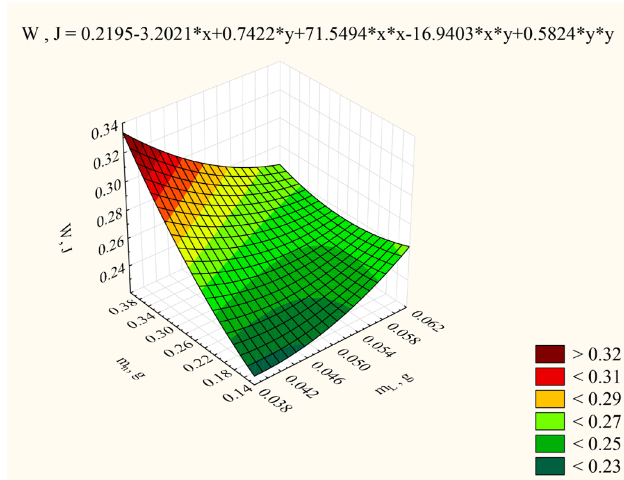


Fig. 14. Ratio of nut mass (m_n), load mass (m_L) and destruction energy (W)

These findings demonstrate that surface roughness parameters significantly influence the energy required for shell fracture. Further research will focus on refining the geometric characteristics of the impact surface to enhance processing efficiency while minimizing kernel damage.

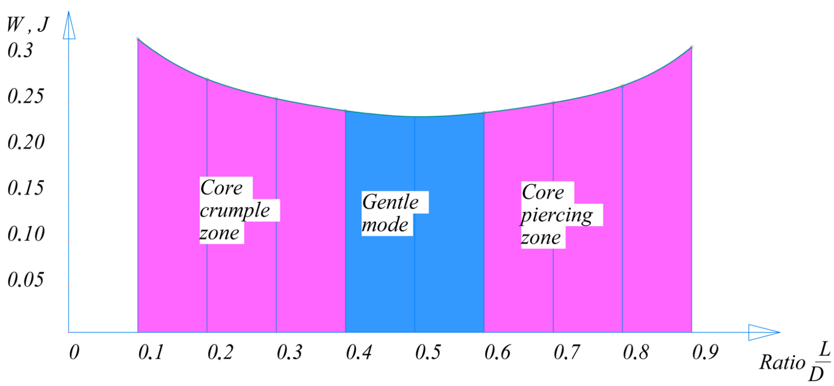


Fig. 13. Influence of the L/D ratio on the impact energy required for pine nut shell fracture

Table 2

Impact energy for pine nut shell fracture as a function of load mass and drop height

No.	Load mass m_L, kg	Height H, m	Load velocity load V_L, m/s	Energy W, J	Nut mass m_n, g	Nut velocity V, m/s
1	0.04	0.58	3.3734	0.2276	0.15	55.09
2	0.04	0.6	3.4310	0.2354	0.17	52.63
3	0.04	0.59	3.402323	0.2315	0.18	50.72
4	0.04	0.62	3.4877	0.2433	0.19	50.61
5	0.05	0.5	3.1321	0.2453	0.22	47.22
6	0.05	0.5	3.1321	0.2453	0.23	46.18
7	0.05	0.51	3.1633	0.2502	0.26	43.87
8	0.05	0.51	3.1633	0.2502	0.27	43.05
9	0.06	0.43	2.9046	0.2531	0.29	41.78
10	0.06	0.44	2.9382	0.2590	0.33	39.62
11	0.06	0.44	2.9382	0.2590	0.34	39.03
12	0.06	0.45	2.971363	0.2649	0.38	37.34

5. 4. Development of a device for pine nut shell fracture

It is essential to consider that, in general, the impact occurs tangentially to the curve forming the nut shell. Therefore, final conclusions can only be drawn after conducting experiments with the working equipment.

Currently, various methods and devices are used for breaking the nut shell to extract its kernel. The simplest method involves crushing the nut in roller crushers [14, 15]. However, this method requires careful preliminary sorting of the nuts by size. Other methods include grinding the narrow ends of the nut to reduce its strength by removing the closed nature of the spherical shell.

Analysis of existing methods and devices shows that the most acceptable method in terms of providing a gentle fracture mode is the acceleration of the nuts to a velocity that causes the shell to fracture, with the mass then impacting an obstacle in the form of a striking plate [16].

This device for extracting pine nut kernels has the following features:

– since accelerating the nuts to a velocity that causes the shell to fracture requires a significant length of the pipeline, it is designed as sinusoidal;

– the loading hopper is sealed, and to maintain constant air pressure, sluice and electromagnetic valves are installed;

– the jet stream mold is cone-shaped to achieve the velocity necessary to break the hut shell;

– the working hopper is equipped with a riffled striking plate set at a specific angle.

However, a major drawback of this device is its periodic operation. That is, after the chamber is emptied, it requires air pressure release and reloading with a new batch of nuts. Additionally, accelerating the nuts to the required fracture velocity demands a large volume of air and a long pipeline. The installation of sluice and electromagnetic valves in the loading hopper complicates the device. Since the nuts are pre-treated with steam and have increased moisture content, nut residue clumps can accumulate at the bottom of the chamber, which the airflow cannot dislodge. Applying air pressure from above the entire mass of nuts leads to an uneven mixture of air and nuts, which can result in a high consumption of compressed air.

To eliminate these shortcomings, a device for cracking pine nut shells was developed and patented [17] (Fig. 15), which includes a loading hopper, pipeline, acceleration block, jet stream mold, working hopper with a striking plate, and receiving container. This device is distinguished by the following features: the loading hopper allows for continuous loading, a rotating toothed disc in a vertical plane is used for preliminary acceleration of the nut flow, instead of a long sinusoidal pipeline, a short pipeline with nozzles is used to deliver compressed air.

When accelerating the nuts to the fracture velocity, challenges arise because the nut has a spherical shape and therefore has low drag, in addition to its high density. Consequently, a significant amount of air at high pressure is needed to accelerate the nut from rest to the required velocity. Flow stabilization of the air-nut mixture occurs after the nut reaches its floating velocity.

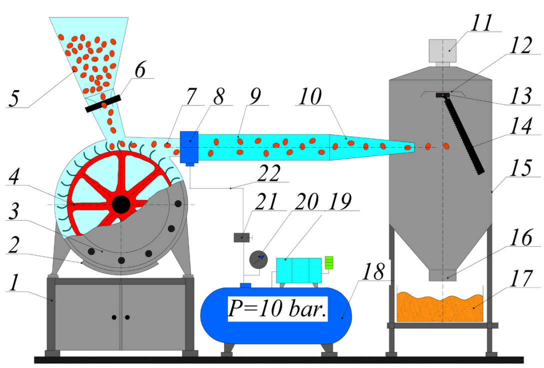


Fig. 15. Schematic of the device for gentle nut shell fracture: 1 – frame; 2 – technological hatch; 3 – acceleration block cover; 4 – toothed wheel; 5 – receiving hopper; 6 – regulating diaphragm; 7 – nuts accelerated to floating velocity; 8 – compressed air supply device; 9 – flow mold; 10 – accelerator; 11 – filter; 12 – screen; 13 – mechanism for angle adjustment; 14 – riffled striking plate; 15 – destructor casing; 16 – discharge sluice; 17 – discharge container; 18 – receiver; 19 – compressor; 20 – pressure gauge; 21 – regulating valve; 22 – air duct

In the proposed device, the acceleration of the pine nut takes place in two stages. On the first stage, the nuts are accelerated to floating velocity mechanically, using a rotating, vertically positioned toothed disc. On the second stage, the accelerated nuts are caught by the air stream and further accelerated to a velocity that exceeds the energy required to fracture their shells.

The device for pine nut shell fracture consists of an electric motor, with a vertical toothed disc mounted on its shaft. The space between the teeth allows the nuts to fit freely inside. The diameter of the dividing circle and the motor velocity are selected so that the linear velocity of the nuts exceeds the floating velocity. The nut, moving at this velocity, enters the air intake block, where compressed air is supplied under high pressure through nozzles directed along the air-sleeve. Once the air-nut mixture flow stabilizes, it passes into the flow mold, where the flow velocity is increased to the required velocity. The exit of the flow mold is directed into the working hopper, which is equipped with a striking plate, a conical bottom, and an exit nozzle under which the receiving container is installed.

Device operation. After hydrothermal treatment, the pine nuts continuously flow into the device's intake chamber 1. Simultaneously, the compressor is turned on, and compressed air is supplied under high pressure through the receiver 18, into the intake pipeline. The special compressed air supply device 8 (Fig. 16) has nozzles directed in the flow direction of the air-nut mixture.

At the same time, the electric motor starts, and the toothed disc 4 begins to rotate at the preset velocity. The rotational velocity of the disc is controlled by the vector frequency converter. The flow of nuts, formed using the adjustable diaphragm 6, enters the grooves between the teeth of the rotating disc and is launched into the intake pipeline at a velocity that exceeds the floating velocity.

In the intake pipeline, the nut and air streams mix uniformly, and the air-nut mixture flow stabilizes. To prevent air from flowing back towards the toothed disc and intake chamber, the air stream is directed through the nozzles. After the intake pipeline 9, the mixture enters the flow mold 10, where the velocity of the flow is increased to the required level. Then, the air-nut mixture flows towards the striking plate 14, and the nut shells break apart. The mixture of nut kernels and shell fragments falls through the conical bottom into the receiving container 17.

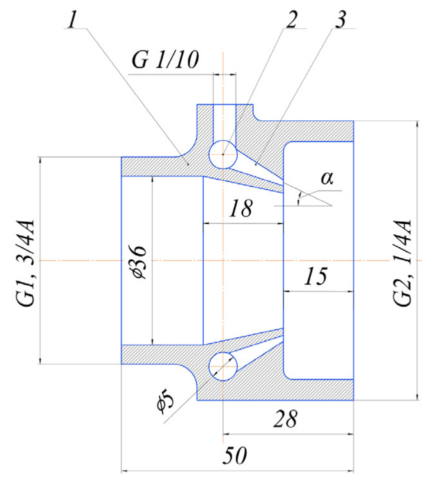


Fig. 16. Compressed air supply device: 1 – housing; 2 – annular channel; 3 – nozzle

The use of this device allows for an increase in the output of finished products and the quality of extracted nut kernels, while preserving their integrity, nutritional value, and pharmaceutical properties. The device can be easily implemented in both the food and pharmaceutical industries.

6. Discussion of the results of pine nut shell fracture and processing efficiency

This section aims to interpret the findings in relation to the research objectives and to compare the proposed method with existing technologies, highlighting the advantages, limitations, and potential for future development.

According to the first objective of this study, a static analysis of pine nut shell fracture was conducted using three types of indenters. The results (Fig. 6–9) indicated that the 90° cone indenter provided the most effective shell rupture while minimizing kernel damage. Under optimal conditions nut size of 10.8–11.4 mm and moisture content of 15–16% the average fracture force reached 49 N with a deformation of 1.1–1.3 mm, resulting in a calculated fracture energy of 0.245 J. This outcome confirms the importance of maintaining moisture within a specific range to ensure fracture with minimal damage, as lower or higher moisture levels lead to brittle failure or excessive softening, respectively.

In addressing the second objective, a theoretical model of the shell was developed based on thin-walled spherical shell mechanics. Using finite element analysis (Fig. 10), stress distribution and shell displacement were calculated under a concentrated force of 50 N. The maximum displacement was found to be 0.016 mm, and the stress was uniformly distributed, indicating predictable fracture behavior. These results correlate with the experimental data, confirming the reliability of the model for predicting the fracture threshold and guiding the design of energy-efficient processing equipment.

For the third objective, the study investigated shell strength under impact loads using a pendulum-based test stand. Results (Table 2, Fig. 13, 14) showed that effective shell cracking occurs at an impact velocity of 35–40 m/s. A key finding was that the roughness of the impact surface had a significant effect: a surface with an L/D ratio of 0.4–0.6 reduced the fracture energy by 10–15% by concentrating stress at specific points and initiating cracks more efficiently. This demonstrates how modifying contact geometry can contribute to energy savings and reduce mechanical damage.

The fourth objective involved the development and testing of a novel two-stage acceleration device combining a rotating toothed disk and a high-velocity compressed air stream. The pre-acceleration stage ensured that the nuts reached floating velocity before being further accelerated to the optimal impact velocity. This configuration led to a 15–20% increase in whole kernel yield and a 10% reduction in energy consumption. In contrast to traditional roller crushers [14, 15], which rely on calibrated nut sizes and cause significant kernel breakage, the proposed device allows for continuous operation without prior sorting. Unlike thermal treatment methods [2], which may compromise the nutritional quality of the kernel, our method achieves mechanical shell rupture without excessive heating. Additionally, in comparison to pneumatic systems analyzed in [4], our device improves efficiency by stabilizing the airflow and using mechanical pre-acceleration, thereby reducing compressed air requirements.

Compared to the methods in [9], which involved compressive loading that often resulted in uneven fracture and kernel puncture, our approach ensures a uniform stress distribution confirmed by FEM simulations and a cleaner break. While multi-point extrusion cracking for walnuts is described in [14], our method is tailored to pine nuts, which present different geometrical and mechanical challenges. Unlike [7], where precise energy thresholds were identified for controlled fracture, our study not only determines the required energy but also provides a practical mechanical design that delivers the necessary impact in a continuous process.

The developed system minimizes energy use, increases kernel yield, and eliminates the need for time-consuming size calibration. These findings contribute to the advancement of pine nut processing technologies by improving shell-breaking efficiency, reducing energy costs, and optimizing kernel extraction. The proposed method and developed device have the potential for application in the food and pharmaceutical industries, ensuring sustainable and cost-effective processing solutions.

However, certain limitations must be considered. The experiments were conducted under laboratory conditions and may not fully replicate industrial environments. The system was tested on a single pine nut variety and under specific moisture conditions. The current version of the device operates in semi-continuous mode and may require modifications to support uninterrupted industrial processing. Moreover, air pressure fluctuations and potential clogging due to moist residue buildup in the chamber could affect operational stability.

The study also has several shortcomings. For instance, it does not yet incorporate automatic feedback control systems or real-time quality monitoring. The airflow-nut trajectory must be carefully aligned, and variations in nut size could introduce inconsistencies. Maintenance demands may increase over long-term use due to dust and shell fragment accumulation.

Future research will focus on scaling the device for industrial testing, automating process control (e.g., airflow regulation and rotation velocity), and testing the system across a broader range of nut types and moisture levels. Integration of computer vision and AI tools for kernel quality assessment is also a promising direction. Modular redesign could allow adaptation to existing nut processing lines, enhancing commercial viability.

7. Conclusion

1. A static analysis of pine nut shell cracking was conducted using three types of indenters (Tarr-Baker, 45° cone, and 90° cone). The results demonstrated that the 90° cone indenter was the most effective for controlled shell fracture, achieving an optimal balance between applied force and kernel protection. The ideal moisture cement for minimal damage was determined to be 15—16%.

2. A theoretical model for pine nut shell strength under impact loads was developed. Calculations based on fracture mechanics principles allowed for the determination of the energy required for shell breaking, which was validated through experimental testing. The fracture energy for pine nut shells was found to be 0.245 J under an impact force of 49 N and a deformation range of 1.1—1.3 mm.

3. The mechanical properties of pine nut shells under impact loads were investigated using a pendulum-based test rig. The optimal impact velocity for effective shell fracture was identified as 35—40 m/s. Additionally, the use of a roughened impact surface with a T/D ratio of 0.4—0.6 reduced fracture energy by 10—15%, contributing to a more efficient cracking process.

4. A novel device for pine nut shell fracture was designed and developed, incorporating a two-stage acceleration method. The combination of a rotating toothed disk for pre-acceleration and a compressed air stream to achieve the required impact velocity resulted in an increase in whole kernel yield by 15–20%, a 10% reduction in energy consumption, and minimized kernel damage compared to traditional mechanical crushing methods.

Conflicts of interest

The authors declare that there are no conflicts of interest.

Financing

The study was performed without financial support.

Data availability

The data supporting the findings of this study are available from the corresponding author upon request, subject to reasonable terms.

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Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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