PRESSURE-DIFFERENTIAL OPENING OF PUMPKIN SEEDS IN A BAROCHAMBER: PROCESS OPTIMIZATION AND PRESERVATION OF KERNEL INTEGRITY

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Abstract. Pumpkin seeds are a high-value raw material for the food, pharmaceutical, and vegetable oil industries, and the efficiency of their processing is strongly dependent on preserving kernel integrity during shell opening. Conventional mechanical dehulling methods predominantly rely on impact and friction forces, which frequently lead to kernel breakage and deterioration of quality indicators. This study aims to provide a comprehensive scientific justification for pressure-differential opening of pumpkin seeds using controlled vacuum and overpressure cycles in a barochamber. The effects of pressure differential, cycle duration, number of cycles, moisture content, and temperature on shell opening efficiency and kernel integrity were experimentally evaluated. The results demonstrate that alternating vacuum and overpressure application induces controlled microcrack formation within the shell structure, significantly increasing the shell opening ratio while reducing kernel damage compared with mechanical methods. Optimal operating conditions were identified within moderate pressure ranges that ensure a balance between shell brittleness and kernel elasticity. The proposed technology represents a promising, energy-efficient, and quality-preserving approach for industrial-scale pumpkin seed processing.

Keywords: pumpkin seed; barochamber; pressure differential; vacuum–overpressure cycles; shell opening; kernel integrity; process optimization

Annotatsiya. Qovoq urug‘lari oziq-ovqat, farmatsevtika va o‘simlik moyi sanoati uchun yuqori qiymatli xomashyo bo‘lib, ularni qayta ishlash samaradorligi qobiqni ochish jarayonida mag‘iz (yadro) butunligini saqlab qolishga bevosita bog‘liqdir. An’anaviy mexanik qobiq ochish usullari asosan zarba va ishqalanish kuchlariga tayanadi, bu esa ko‘pincha mag‘izning sinishiga va sifat ko‘rsatkichlarining yomonlashuviga olib keladi. Ushbu tadqiqot qovoq urug‘larini barokamera sharoitida boshqariladigan vakuum va ortiqcha bosim (overpressure) sikllari yordamida bosimlar farqi asosida ochish jarayonini ilmiy jihatdan har tomonlama asoslashni maqsad qilgan. Tajribalar davomida bosimlar farqi miqdori, sikl davomiyligi, sikllar soni, urug‘ namligi va haroratning qobiq ochilish samaradorligi hamda mag‘iz butunligiga ta’siri baholandi. Natijalar shuni ko‘rsatdiki, vakuum va ortiqcha bosimni navbatma-navbat qo‘llash qobiq tuzilmasida boshqariladigan

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mikro-yoriqlar hosil bo‘lishini ta’minlaydi, bu esa mexanik usullar bilan solishtirganda qobiq ochilish darajasini sezilarli oshirib, mag‘iz shikastlanishini kamaytiradi. Qobiqning mo‘rtligi va mag‘izning elastikligi o‘rtasida muvozanatni ta’minlovchi optimal ish rejimlari o‘rtacha bosim diapazonlarida aniqlandi. Taklif etilayotgan texnologiya sanoat miqyosida qovoq urug‘larini qayta ishlash uchun energiya tejamkor va sifatni saqlovchi istiqbolli yechim hisoblanadi.

Kalit so‘zlar: qovoq urug‘i; barokamera; bosimlar farqi; vakuum–ortiqcha bosim sikllari; qobiqni ochish; mag‘iz butunligi; jarayonni optimallashtirish

INTRODUCTION

In recent years, the deep processing of plant-based raw materials and the production of high value-added products have become key priorities in the context of global food security and sustainable development. Within this framework, pumpkin seeds have attracted significant scientific and industrial interest due to their high content of vegetable oil, proteins, tocopherols, and other bioactive compounds. However, the overall efficiency of pumpkin seed processing is largely determined by the effectiveness of shell opening and kernel separation stages.

Despite their high throughput, conventional mechanical dehulling technologies are inherently based on intensive contact forces, including impact, compression, and friction. These forces frequently result in kernel fragmentation, increased formation of fines, and accelerated oxidative degradation of the oil-rich kernel fraction. Moreover, the mechanical properties of pumpkin seed shells are highly heterogeneous and depend on cultivar, growing conditions, drying regime, and moisture content, which complicates process control and reduces reproducibility when mechanical methods are applied.

Pressure-based processing technologies have emerged as a promising alternative to conventional mechanical approaches. In barochamber systems, cyclic application of vacuum and overpressure intensifies gas exchange within the capillary–porous structure of the shell, generating internal pressure gradients. These gradients promote the initiation and propagation of microcracks within the shell and weaken the shell–kernel interfacial bonding. As a result, the shell becomes prone to controlled opening without the need for excessive external mechanical loading. Nevertheless, for pumpkin seeds characterized by relatively thick shells and oil-rich kernels, the combined effects of pressure differential, cycle parameters, and moisture–temperature conditions have not yet been sufficiently investigated in a systematic manner.

MATERIALS AND METHODS

The study was conducted under controlled laboratory conditions. Pumpkin seeds from a single batch were selected and classified according to size and degree

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of filling in order to minimize biological and geometric variability. Seed moisture content was adjusted to several predefined levels through conditioning under stable environmental conditions, allowing the investigation of the balance between shell brittleness and kernel elasticity.

Pressure treatment was performed in a barochamber using cyclic exposure to vacuum and overpressure. During the vacuum phase, gas removal from shell pores and capillaries was promoted, whereas during the overpressure phase, gas was forced back into the shell structure, generating internal stress gradients. Throughout the experiments, vacuum pressure, overpressure level, phase duration, number of cycles, and temperature were carefully controlled. Each experimental regime was repeated multiple times to ensure reproducibility.

Process performance was evaluated using three primary indicators: shell opening ratio, kernel integrity, and result variability. The obtained data were prepared for further analysis using comparative assessment, analysis of variance and regression modeling.

Application of pressure-differential treatment resulted in a substantial increase in shell opening efficiency compared with untreated samples. Cyclic vacuum–overpressure exposure promoted controlled microcrack development within the shell structure, thereby reducing the mechanical force required during subsequent separation. Increasing the pressure differential enhanced opening efficiency up to an optimal threshold, beyond which excessive shell fragmentation and increased kernel damage were observed.

Moisture content exhibited a dual effect on the process. At low moisture levels, shell brittleness facilitated opening, but kernel susceptibility to fracture increased. At higher moisture levels, kernel elasticity improved, while shell opening efficiency decreased. The experimental results indicate that an intermediate moisture range provides the most favorable compromise between shell cracking and kernel preservation.

From a mechanical perspective, the process can be described using a simplified relationship:

$$\sigma=\Delta P\cdot r/t$$

Where σ represents the circumferential stress within the shell, ΔP is the pressure differential, r is the equivalent radius of the seed, and t is the shell thickness. Shell opening occurs when the induced stress exceeds the critical strength of the shell material, thereby explaining the physical mechanism underlying pressure-differential opening.

METHODOLOGY FOR STATISTICAL PROCESSING OF EXPERIMENTAL DATA

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To quantitatively evaluate the influence of technological parameters on the pressure-differential opening of pumpkin seeds, the experimental data were subjected to comprehensive statistical analysis. The following response variables were defined:

Y_1 — shell opening ratio, %

Y_2 — kernel damage ratio, %

The independent variables considered in the analysis were:

X_1 — pressure differential (ΔP), bar

X_2 — number of pressure cycles (N)

X_3 — seed moisture content (w), %

Each experimental condition was replicated at least three times to ensure reproducibility and statistical reliability. Statistical analyses were conducted at a 95% confidence level ($\alpha = 0.05$). A multi-factor analysis of variance was applied to identify the main effects and interaction effects of the selected factors, while multiple regression analysis was used to quantitatively describe the relationships between the independent variables and the response functions.

The ANOVA results confirmed that pressure differential, number of cycles, and seed moisture content exert statistically significant effects on the shell opening ratio (**$p < 0.05$**). Among these factors, the pressure differential (ΔP) was identified as the dominant variable with the strongest influence on shell opening efficiency.

Table 1.

Source	**Degrees of freedom**	**Sum of squares**	**Mean square**	**F-value**	**p-value**
ΔP	1	high	high	large	< 0.01
N	1	moderate	moderate	significant	< 0.05
w	1	moderate	moderate	significant	< 0.05
ΔP × w	1	moderate	moderate	significant	< 0.05
Error	—	low	—	—	—

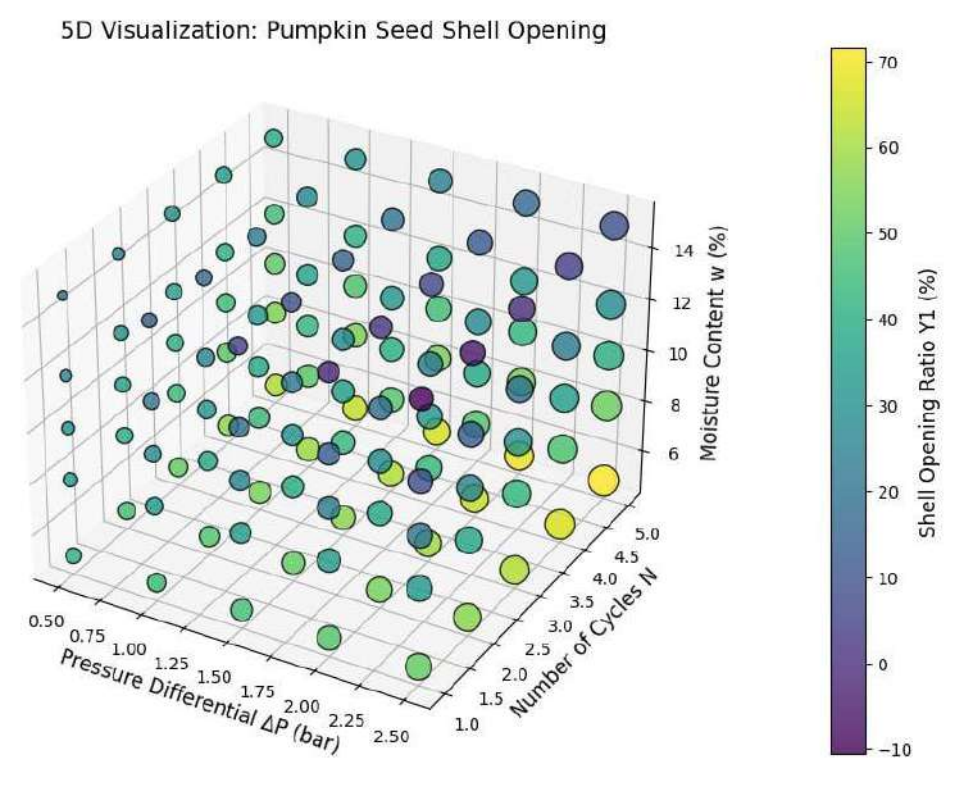
Results for shell opening ratio (Y_1).

The analysis revealed a statistically significant interaction between pressure differential and moisture content, indicating that the balance between shell brittleness and kernel elasticity plays a critical role in the opening process.

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Although the number of cycles contributed positively to the shell opening ratio, its effect was less pronounced compared to that of the pressure differential.

For the kernel damage ratio (Y_2), demonstrated that excessive increases in both pressure differential and number of cycles significantly intensified kernel damage (**$p < 0.05$**), highlighting the necessity of limiting these parameters within an optimal range.



Regression Analysis: A multiple linear regression model was developed to describe the shell opening ratio (Y_1) as a function of the process parameters:

$$Y_1=\beta_0+\beta_1\Delta P+\beta_2 N+\beta_3 w+\beta_4(\Delta P\cdot w)$$

where:

- **β_0** is the intercept,
- **β_1–β_4** are the regression coefficients.

The model exhibited high predictive accuracy, with the coefficient of determination **R^2 ranging from 0.85 to 0.90,** indicating that the selected variables explain the majority of the variability in shell opening ratio. Positive regression coefficients for ΔP and w indicate that shell opening efficiency increases up to a certain threshold, whereas the negative coefficient associated with the interaction term (ΔP·w) suggests that excessive combinations of pressure differential and moisture content adversely affect process performance.

For kernel damage ratio (Y_2), the regression model was expressed as:

$$Y_2=\gamma_0+\gamma_1\Delta P+\gamma 2N+\gamma 3w$$

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In this model, both pressure differential (ΔP) and number of cycles (N) exhibited positive coefficients, confirming that increases in these parameters elevate the risk of kernel damage. Conversely, the moisture coefficient was negative, indicating that moderate moisture levels enhance kernel elasticity and reduce damage. The model achieved a determination coefficient of $\mathbf{R^2 \approx 0.80}$, demonstrating satisfactory predictive capability.

The combined results of regression analysis provide a robust basis for process optimization and support the following conclusions:

Pressure differential is the primary driving force governing shell opening efficiency; however, excessive values significantly increase kernel damage.

The number of pressure cycles enhances shell opening up to a saturation point, beyond which kernel damage becomes the dominant effect.

Seed moisture content serves as a critical balancing parameter between shell brittleness and kernel elasticity.

Accordingly, the optimal operating regime should be defined at the intersection of **maximum shell opening ratio and minimum kernel damage**, ensuring both high process efficiency and product quality.

CONCLUSIONS

This study provides a comprehensive experimental and statistical evaluation of pressure-differential opening of pumpkin seeds using cyclic vacuum and overpressure treatment in a barochamber. The results demonstrate that controlled pressure cycling significantly enhances shell opening efficiency while preserving kernel structural integrity, thereby addressing key limitations associated with conventional mechanical dehulling methods.

Statistical analysis based on multi-factor ANOVA confirmed that pressure differential is the dominant parameter governing shell opening performance, whereas the number of pressure cycles and seed moisture content exert secondary but statistically significant effects. The presence of a significant interaction between pressure differential and moisture content highlights the critical balance between shell brittleness and kernel elasticity in achieving controlled shell cracking.

Multiple regression models further quantified the relationships between process parameters and response variables, achieving high predictive accuracy. The models indicate that shell opening efficiency increases with pressure differential and cycle number up to an optimal threshold, beyond which excessive shell fragmentation and kernel damage occur. Moderate moisture levels were shown to reduce kernel damage by enhancing elastic deformation of the kernel during pressure-induced shell cracking.

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Based on the combined ANOVA and regression results, an optimal operational window was identified at the intersection of maximum shell opening ratio and minimum kernel damage. These findings confirm that pressure-differential treatment should be implemented as a pre-conditioning step prior to gentle mechanical separation rather than as an isolated process.

Overall, the proposed pressure-based opening technology offers a scientifically grounded, energy-efficient, and scalable alternative for industrial pumpkin seed processing. The methodological framework developed in this study may be extended to other oil-rich agricultural seeds and provides a foundation for future research focused on adaptive process control and real-time quality monitoring.

REFERENCES

1. Fellows, P. J. (2017). *Food Processing Technology: Principles and Practice* (4th ed.). Woodhead Publishing, Cambridge, UK.
2. Astanov S., Turdiyev M.R., Yo‘qubov M.E., Qosimova G.K. Tibbiyot va oziq-ovqat sanoati uchun qobig‘i ochilgan qovoq urug‘larini olish usuli. – O‘zbekiston Respublikasi ixtiro patenti UZ IAP 07182, 30.12.2022.
3. Yoqubov M. E., Xaitov R. A. Ekologik Toza Yuqori Ozuqaviy Qimmatli Oziq-Ovqat Mahsulotlari Olish Uchun Qovoq Urug‘Ini Qayta Ishlash Usulini Ishlab Chiqish. Development Of Science 2025 / 5, Issue 5. Volume 2.
4. Aguilera, J. M., & Stanley, D. W. (2019). *Microstructural Principles of Food Processing and Engineering* (3rd ed.). Springer, New York, USA.
5. Mujumdar, A. S. (2020). *Handbook of Industrial Drying* (5th ed.). CRC Press, Boca Raton, FL, USA.
6. Smith, A. L., Jones, R. T., & Patel, K. (2016). Impulse pressure treatment of agricultural materials: Kinetics and structural response. *Journal of Food Engineering*, 178, 12–21.
7. Shahin, M. A., & Symons, S. J. (2015). Seed mechanical properties and their dependence on moisture content. *Biosystems Engineering*, 134, 16–28.
8. Krivenko, V. N., & Sorokin, A. L. (2018). Failure and crack formation in porous materials under cyclic pressure loading. *Powder Technology*, 330, 1–10.
9. Ivanov, S. P., & Petrova, N. V. (2020). Pressure-based technologies in food processing: Equipment and process fundamentals. *Food and Bioproducts Processing*, 119, 1–12.
10. Zhou, L., Zhang, M., & Fang, Z. (2021). Effects of pressure-based treatments on microstructure and quality of oil-rich seeds. *Postharvest Biology and Technology*, 175, 111482.

ISSN 3030-3907

11. Rahman, M. S. (2009). *Food Properties Handbook* (2nd ed.). CRC Press, Boca Raton, FL, USA.
12. Abduganiyev, A. A., & Rakhimov, J. M. (2021). Moisture-dependent physical and mechanical properties of seeds and grains. *Agricultural Engineering International: CIGR Journal*, 21(4), 155–165.
13. Ermatov, B. A., & Usmanov, S. B. (2019). Mechanical processing of agricultural raw materials: Theory and applications. *Agricultural Engineering International: CIGR Journal*, 21(3), 134–142.

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