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RESULTS OF EXPERIMENTAL STUDIES OF A CASTOR SEED CLEANING MACHINE

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The study addresses the pressing issue of improving the efficiency of post-harvest processing of castor (Ricinus communis), particularly the cleaning of its seeds. Castor is a valuable industrial crop, the seeds of which contain up to 50% oil that is widely used across various industries. Despite the growing demand for castor oil, the widespread introduction of this crop into agricultural production is hindered by the lack of effective technical means for seed cleaning, which would take into account its specific physical and mechanical properties. Existing grain cleaning machines are insufficiently effective for processing castor seeds, resulting in significant losses of planting material and reduced oil yield.

The aim of the research is to develop an experimental prototype of a machine for cleaning castor seeds and to determine the optimal operating parameters. The study presents the design and working principle of the experimental setup, which consists of a mechanical seed separation unit, an aerodynamic cleaning system, and a control system with a frequency converter. To evaluate the performance of the machine, experimental studies were conducted in which the following parameters were varied: the distance between the crushing cones, their rotational speed, and the air flow velocity.

As a result of the experimental studies of the processes of seed separation and cleaning, the dependencies of the main operational indicators of the developed machine – productivity Q, power consumption P, specific energy consumption E, share of unhulled fruits ξ_f*, and content of valuable seed in the receiver* $\psi_{s\text{-}s}$ *– on the design and operating parameters (distance between the return and crushing cones δ, rotational speed of the crushing cone n, and air flow velocity V) were determined. Statistical analysis of the obtained regression equations allowed for the assessment of the influence of each studied factor on the output indicators, identification of the most significant parameters, and development of adequate mathematical models.*

Parameter optimization was carried out using the scalar ranking method with minimization of a multiplicative objective function in the Wolfram Cloud environment. This made it possible to determine the optimal values of control parameters (δ = 10.8 mm; n = 563 rpm; V = 3.6 m/s) that provide the best combination of energy efficiency and technological quality of the process (E = 0.0394 MJ/kg; Q = 163.4 kg/h; P = 1861 W; $\xi_f = 0.099$*;* $\psi_{s\text{-}s} = 0.958$*). The obtained results confirm the efficiency of the proposed machine design and the feasibility of its further implementation in industrial conditions for cleaning castor seeds.*

Key words*: castor, seed cleaning, fruits, post-harvest processing, agricultural machinery, energy efficiency, crushing cone, aerodynamic cleaning, experimental research, regression analysis, parameter optimization, productivity, rotational speed, air flow velocity.*

Eq. 7. Fig. 5. Ref. 15.

1. Problem formulation

Under the current conditions of development of Ukraine's agro-industrial complex, the implementation of new technologies and technical means for the efficient processing of non-traditional oilseed crops, particularly castor bean, is gaining increasing importance [1, 2]. Castor bean (Ricinus communis) is a valuable industrial crop whose seeds contain up to 50% oil, which is used in the chemical, pharmaceutical, aviation, food, and mechanical engineering industries [3]. The demand for castor oil as an environmentally friendly and multipurpose product is growing both in domestic and international markets [4].

However, the widespread adoption of castor bean cultivation in agricultural production is hindered by insufficient technical support for its post-harvest processing, especially seed cleaning. Existing seed cleaning machines often fail to account for the specific physical and mechanical properties of castor seeds, leading to damage, reduced quality of planting material, and lower oil yield during subsequent processing [5].

Therefore, there is a need to develop and improve castor seed cleaning machines that ensure high performance, effective cleaning quality, and minimal loss of valuable material. Experimental studies of such machines are critically important for the scientific justification of their design, operating modes, and further implementation in production [6]. This will not only enhance the efficiency of castor processing but also contribute to the development of national seed production, energy independence, and environmental safety.

2. Analysis of recent research and publications

A significant number of studies have been devoted to analyzing the performance of existing grain cleaning machines (separators, trieurs, pneumatic separators) [7–9]. However, most of these machines are designed for traditional crops such as wheat, corn, and sunflower, and do not provide adequate efficiency when working with castor beans. Some publications [10, 11] present the results of attempts to adapt known designs to meet the requirements of castor seed cleaning, but the results obtained require further investigation and experimental validation.

Despite the existence of several studies [12, 13] addressing certain aspects of post-harvest processing of castor bean, comprehensive research on the seed cleaning process—accompanied by the development and experimental substantiation of an efficient machine for this purpose—remains insufficiently explored. Therefore, research aimed at creating a specialized castor seed cleaning machine, taking into account its morphometric characteristics and mechanical sensitivity, is highly relevant and has both scientific and practical significance.

3. The purpose of the article

The aim of the study is to develop an experimental prototype of a castor seed cleaning machine and to determine the main operating patterns and optimal process parameters.

4. Results and discussion

The test bench for studying the castor seed cleaning machine (Fig. 1) is designed for the experimental investigation of the process of separating seeds from the fruit and subsequently cleaning them from impurities, followed by their classification into appropriate fractions. Structurally, the bench is a system of interconnected units mounted on a rigid frame, which ensures stable fixation of the equipment and operational stability. Raw material is fed through a loading hopper, from where the mixture of castor fruits enters the seed separation unit. The main components of this unit are the crushing and counter cones, mounted inside a housing with an internal lining (Fig. 2).

Fig. 1. Test bench for studying the castor seed cleaning machine:

1 – frame; 2 – castor seed separation system; 3 – loading hopper; 4 – aerodynamic cleaning system; 5 – pneumatic separation channel; 6 – cyclone; 7 – centrifugal fan; 8 – fan electric motor; 9 – main electric motor; 10 – seed collector; 11 – unhulled fruit collector; 12 – capsule particle collector; 13 – fine particles and dust collector; 14 – control unit; 15 – Danfoss Micro Drive frequency converter

The mechanical interaction between the crushing elements, which ensures the breakdown of fruits and the release of seeds, is adjusted using a screw mechanism that allows variation of the gap between the cones. The rotation of the crushing mechanism is driven by a conical eccentric sleeve-shaft, powered by the main electric motor through a transmission system that includes a bevel gearbox, pulleys, and a belt. The synchronized motion of individual elements is achieved through a chain drive with sprockets. Additionally, the design includes an external lining and a distributor that facilitates uniform feeding into the crushing unit.

After mechanical separation, the mixture is fed into the aerodynamic cleaning system, which consists of a pneumatic separation channel, a fan, and a cyclone. In the pneumatic channel, particles are separated according to their aerodynamic properties: light impurities and dust are removed from the heavier fractions. The airflow is generated by a centrifugal fan driven by a separate electric motor. Light particles are captured in the cyclone and then discharged into dedicated collectors. The system includes collectors for seeds, unhulled fruits, capsule fragments, and fine particles and dust, thus enabling a complete separation cycle.

The operation of the test bench is controlled via a control panel equipped with a Danfoss Micro Drive frequency converter, which enables precise regulation of motor speeds depending on the properties of the input material.

The bench provides the capability for detailed study of cleaning process parameters, adjustment of operating modes, and evaluation of seed separation efficiency from the bulk material.

For conducting experimental studies on the castor seed cleaning test bench, modern measuring instruments were used to ensure accurate determination of the operating process parameters.

The Danfoss Micro Drive frequency converter (VLT® Micro Drive FC 51 series) is employed as part of the test bench for studying the castor seed cleaning machine as a motor control device and simultaneously as a means of measuring the power consumed by the drive during operation. The main measuring device is the multifunctional measuring instrument Solomat MPM500, designed for recording and analyzing airflow parameters. A Benetech GM8905 tachometer was used to monitor the rotational speed of the machine's working parts. To determine the mass of different product fractions obtained during the operation of the castor seed cleaning machine, electronic commercial scales VP1-Tv (BK) were used during the experimental research.

Fig. 2. Individual components of the test bench for studying the castor seed cleaning machine:
1 – counter cone; 2 – crushing cone; 3 – housing with internal lining; 4 – adjustment screw; 5 – sprocket; 6 – chain; 7 – external lining; 8 – distributor; 9 – conical eccentric sleeve-shaft; 10 – bevel gearbox; 11 – driven pulley; 12 – driving pulley; 13 – belt; 14 – main electric motor

The studies were carried out at the Oil Crops Institute of the National Academy of Agrarian Sciences of Ukraine. The factors chosen for the research were the design and technological parameters that most affect the process of separating and cleaning castor seeds: the distance between the counter cone and the crushing cone δ (0–20 mm); the rotational speed of the crushing cone n (400–800 rpm); and the airflow velocity V (2–6 m/s).

The following criteria were selected for the study:

– machine productivity Q (kg/h), determined as the ratio of the mass of the input material to the operation time;

– power consumption of the machine P (W), determined based on data from the frequency converter;

– specific energy consumption E (MJ/kg), calculated as the ratio of power P to productivity Q;

– fraction of unhulled fruits and segments ξf, determined by sampling 300 g in triplicate;

– content of viable seeds in the seed collector ψs-s, determined by sampling 300 g in triplicate.

Experimental studies were conducted according to the Box-Behnken design for three factors, each varied at three levels (a total of 15 experiments). Each experiment was repeated three times, allowing assessment of the factors' effects both individually and in interaction, as well as verification of the adequacy of the resulting mathematical model.

Based on the classical methodology of statistical data processing [14] and the Wolfram Cloud software package [15], second-order regression equations of the dependencies of the study criteria on the factors were calculated.

The regression equation for the productivity of the developed machine Q is as follows (Fig. 3):

$$Q = -110.281 + 0.719514\,n - 0.000562012\,n^2 + 4.93852\,\delta - 0.0568829\,\delta^2, \quad (1)$$

where δ is the distance between the concave and crushing cones, mm; n is the rotational speed of the crushing cone, rpm; V is the air flow velocity, m/s.

The regression equation for the power consumption P of the developed machine is as follows (Fig. 3):

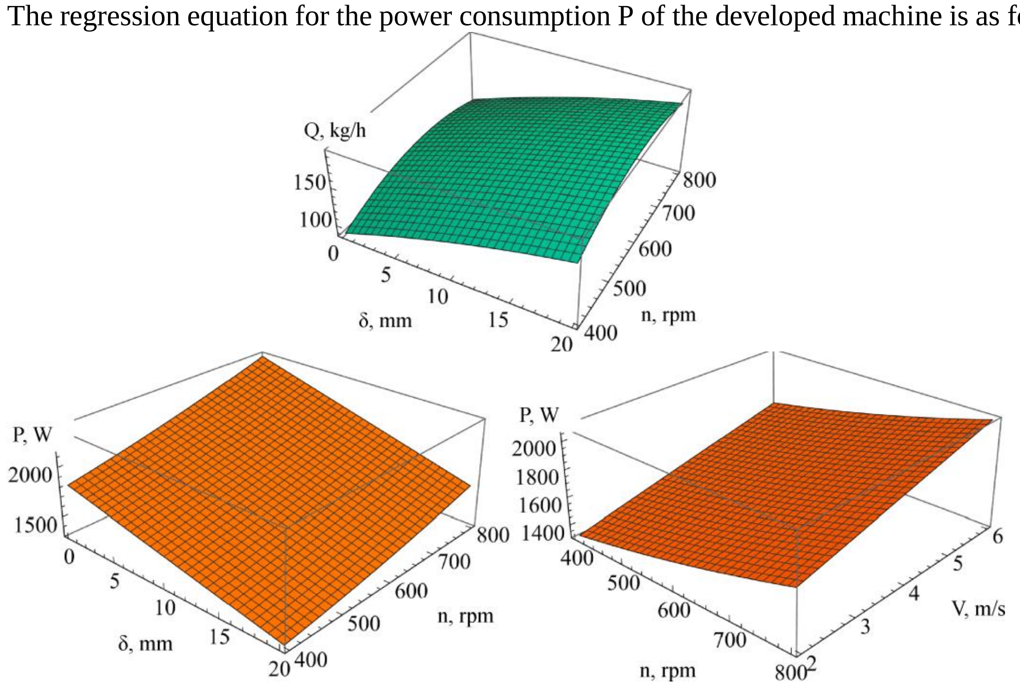

Fig. 3. Dependence of the productivity Q and power consumption P of the developed castor seed cleaning machine on the distance between the concave and crushing cones δ and the rotation speed of the crushing cone n

$$P = 1315.67 + 0.000708\,n^2 + 92.475\,V + 0.518125\,n - 0.01856\,\delta\,n - 17.6425\,\delta. \quad (2)$$

The regression equation for the specific energy consumption E of the developed machine is as follows (Fig. 4):

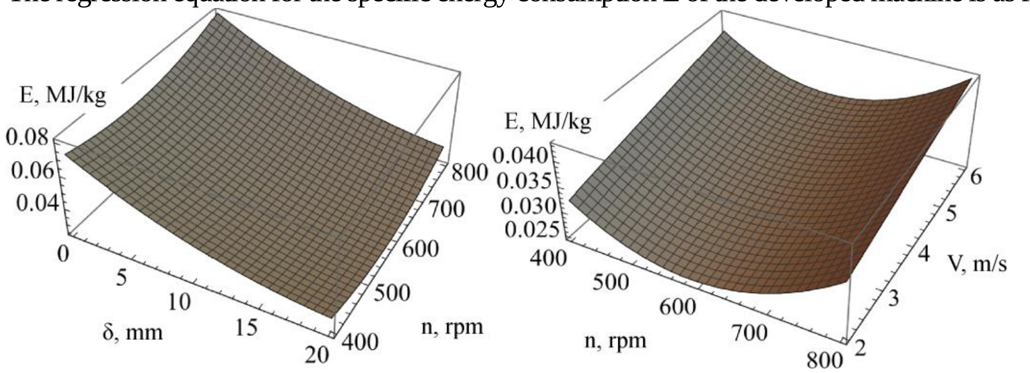

Fig. 4. Dependence of the specific energy consumption E by the developed castor seed cleaning machine on the distance between the concave and crushing cones δ, the rotation speed of the crushing cone n, and the air flow velocity V

$$E = 0.132427 + 2.27395\cdot10^{-7}\,n^2 + 0.00194495\,V - 0.000250877\,n - 6.88955\cdot10^{-7}\,\delta\,n - 0.00331736\,\delta + 0.000079015\,\delta^2. \quad (3)$$

Equation (3) describes a complex but logically justified dependence of the specific energy consumption on the studied factors and allows determining the energetically optimal operating modes of the machine, which ensure effective seed cleaning with minimal energy consumption (E = 0.0246 MJ/kg → δ = 20 mm, n = 582 rpm, V = 2 m/s).

The regression equation for the fraction of unhulled fruits (segments) ξ_f is as follows (Fig. 5):

$$\xi_f = 0.550796 + 1.5326\cdot10^{-6}\,n^2 - 0.00182675\,n + 4.625\cdot10^{-6}\,\delta\,n + 0.00891542\,\delta - 0.000285208\,\delta^2. \quad (4)$$

Overall, to minimize the fraction of unhulled fruits (ξ_f = 0.006), it is necessary to optimize the combination (δ = 0 mm and n = 596 rpm), since their effects are interdependent and nonlinear. Excessive increase of one or both parameters leads to a decrease in process efficiency, which is confirmed by the physical nature of castor fruit crushing.

The regression equation for the content of viable seeds in the seed collector $\psi_{s\text{-}s}$ is as follows (Fig. 5):

$$\psi_{s\text{-}s} = 0.66582 - 4.16042\cdot10^{-7}\, n^2 + 0.000677083\, V^2 + 0.00062715\, n - 9.545\cdot10^{-6}\, \delta\, n - 0.00380917\, V + 0.000125\, \delta\, V + 0.0143342\, \delta - 0.000216417\, \delta^2. \quad (5)$$

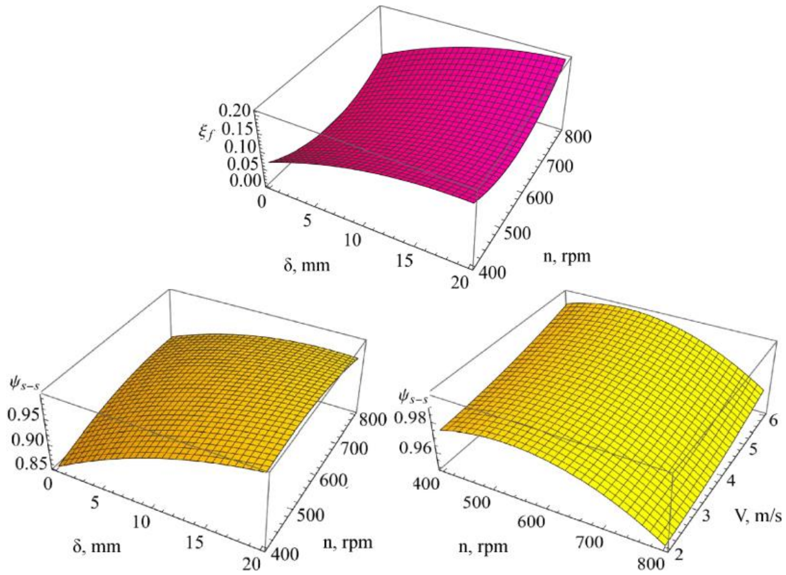

Fig. 5. Dependence of the fraction of unhulled fruits (segments) ξ_f and the content of viable seeds in the seed collector $\psi_{s\text{-}s}$ on the distance between the return and crushing cones δ, the rotational speed of the crushing cone n, and the air flow velocity V

Overall, equation (5) describes a complex nonlinear interaction between the experimental factors, reflecting the physical processes of mechanical destruction of fruit shells, aerodynamic particle separation, and preservation of seed integrity. This allows us to conclude that to achieve the maximum content of viable seeds, it is necessary to ensure an optimal combination of air flow velocity, crushing cone rotation speed, and the distance between the machine's working elements: $\psi_{s\text{-}s}$ = 0.982 → δ = 20 mm, n = 524 rpm, V = 6 m/s.

To optimize the design and technological parameters of the castor seed cleaning machine, we will use the condition of minimizing specific energy consumption and the fraction of unhulled fruits (segments) while maintaining a high content of viable seeds in the seed collector:

$$\begin{cases} E(\delta, n, V) \to \min, \\ \xi_f(\delta, n, V) \to \min, \\ \psi_{s-s}(\delta, n, V) \to \max. \end{cases} \quad (6)$$

Using Wolfram Cloud and the method of minimizing a multiplicative function of the criteria complex obtained through scalar ranking, one of the effective approaches to multi-criteria optimization was implemented. This approach allows finding the best combination of factor values to achieve an optimal result simultaneously across several criteria. Its essence lies in reducing a multi-criteria problem to a single-criterion one by constructing a so-called multiplicative objective function that reflects the interrelationship among all criteria. In cases where it is necessary to optimize multiple functions simultaneously (for example, minimizing specific energy consumption, the proportion of unhulled fruits, and maximizing the content of viable seeds), instead of separately optimizing each criterion, a single aggregated function is used in the form of the product of relative values of each criterion, normalized by the desired or optimal values, taking into account their weights.

The general form of the multiplicative function is:

$$K = \frac{E(\delta, n, V) - E^{\min}}{E^{\max} - E^{\min}} \frac{\xi_f(\delta, n, V) - \xi_f^{\min}}{\xi_f^{\max} - \xi_f^{\min}} \frac{\psi_{s-s}^{\max} - \psi_{s-s}(\delta, n, V)}{\psi_{s-s}^{\max} - \psi_{s-s}^{\min}} \to \min. \quad (7)$$

Solving equation (7) together with (3), (4), and (5), rational values of the design and technological parameters of the castor seed cleaning machine were obtained: δ = 10.8 mm; n = 563 rpm; V = 3.6 m/s → E = 0.0394 MJ/kg; Q = 163.4 kg/h; P = 1861 W; ξ_f = 0.099; $\psi_{s\text{-}s}$ = 0.958.

5. Conclusion

As a result of the experimental studies of the castor seed separation and cleaning process, dependencies were obtained for the productivity of the developed machine Q, the consumed power P, the specific energy consumption E, the fraction of unhulled fruits (segments) ξ_f, and the content of clean seeds in the seed intake $\psi_{s\text{-}s}$ on the distance between the counter and crushing cones δ, the rotational speed of the crushing cone n, and the air flow velocity V. The conducted statistical analysis of the regression equations made it possible to determine the influence of each studied factor on the target performance indicators of the machine, identify significant parameters, and build adequate analytical models.

The application of the scalar ranking method with minimization of the multiplicative function in the Wolfram Cloud environment allowed establishing the optimal combination of factor values (δ = 10.8 mm; n = 563 rpm; V = 3.6 m/s) that ensure maximum process efficiency, taking into account a combination of technological (quality) and energy criteria (E = 0.0394 MJ/kg; Q = 163.4 kg/h; P = 1861 W; ξ_f = 0.099; $\psi_{s\text{-}s}$ = 0.958). The obtained results confirm the feasibility of further implementation of the proposed design of the castor seed cleaning machine in industrial practice.

References

1. Gelfand, I., Sahajpal, R., Zhang, X., Izaurralde, R.C., Gross, K.L., & Robertson, G.P. (2013). Sustainable bioenergy production from marginal lands in the US Midwest. *Nature*, *493*, 514–517. DOI: https://doi.org/10.1038/nature11811 [in English].
2. Alexopoulou, E., Papatheohari, Y., Zanetti, F., Tsiotas, K., Papamichael, I., Christou, M., Namatov, I., & Monti, A. (2015). Comparative studies on several castor (Ricinus communis L.) hybrids: Growth, yields, seed oil and biomass characterization. *Ind. Crops Prod.*, *75*, 8–13. DOI: https://doi.org/10.1016/j.indcrop.2015.07.015 [in English].
3. Román-Figueroa, C., Cea, M., Paneque, M., & González, M.E. (2020). Oil Content and Fatty Acid Composition in Castor Bean Naturalized Accessions under Mediterranean Conditions in Chile. *Agronomy*, *10*, 1145. DOI: https://doi.org/10.3390/agronomy10081145 [in English].
4. Vedmedeva, K.V., Kavyazina, M.Yu., & Makhova, T.V. (2018). Evaluation of castor oilseed samples by economic and valuable characteristics. *Scientific and Technical Bulletin of the Institute of Oilseeds of the NAAS*, *26*, 39–48. https://bulletin.imk.zp.ua/pdf/2018/26/Vedmedeva2_26.pdf [in Ukrainian].
5. Carrino, L., Visconti, D., Fiorentino, N., & Fagnano, M. (2020). Biofuel Production with Castor Bean: A Win–Win Strategy for Marginal Land. *Agronomy*, *10*, 1690. DOI: https://doi.org/10.3390/agronomy10111690 [in English].
6. Tesliuk H.V., Holovchenko V.V. (2025). Analysis of the Design Features of Machines for Castor Seed Cleaning. *Central Ukrainian Scientific Bulletin. Technical Sciences*, 11(42), Part I: 167–176. DOI: https://doi.org/10.32515/2664-262X.2025.11(42).1.167-178 [in English].
7. Aliiev, E.B. (2019). *Physical and mathematical models of the processes of precision separation of sunflower seed material: monograph.* Zaporizhzhia: STATUS. URL: https://aliev.in.ua/doc/knigi/kniga_4.pdf [in Ukrainian].
8. Stepanenko, S.P. (2020). *Mechanical and Technological Justification of the Processes and Equipment for Sieveless Fractionation of Grain Materials:* Doctoral Thesis in Technical Sciences: 05.05.11. Hlevakha. [in Ukrainian].
9. Lupko, K.O. (2023). *Justification of Design and Technological Parameters of a Breeding Seed Indented Cylinder Separator for the Separation of Small-Seeded Crops:* PhD Thesis in Sectoral Engineering: 133 Sectoral Mechanical Engineering. Dnipro. [in Ukrainian].
10. Balami, A.A., Adgidzi, D., Kenneth, C.A., & Lamuwa, G. (2012). Performance Evaluation of a Dehusking and Shelling Machine for Castor Fruits and Seeds. *IOSR Journal of Engineering (IOSRJEN), 2 (10),* 44–48. DOI: https://doi.org/10.9790/3021-021014448 [in English].
11. Yang, L., Chen, H., Xiao, J., Fan, Y., Song, S., Zhang, Y., & Liu, X. (2021). Research on Structural–Mechanical Properties during the Castor Episperm Breaking Process. *Processes*, *9*, 1777. DOI: https://doi.org/10.3390/pr9101777 [in English].
12. Didur, V.V. (2020). *Mechanical and technological foundations of deep processing of castor seeds in the conditions of a small-scale enterprise*: Doctoral Thesis in Technical Sciences: 05.05.11. Melitopol. [in Ukrainian].
13. Yakubu, A.U., Muhammad, U.S., Ishiaka, M., Muhammmad, S.A., & Sale, N.A. (2020). Development and Performance Evaluation of a Castor Seed (Ricnus Communis) Shelling Machine with a Winnowing System. *FUOYE Journal of Engineering and Technology (FUOYEJET), 5 (1),* 2–5. DOI: https://doi.org/10.46792/fuoyejet.v5i1.430 [in English].

14. Kyseliov, O.V., Komarova, I.B., Milko, D.O., & Bakardzhiiev, R.O. (2017). *Statistical Processing and Presentation of Experimental Research Results (Based on the Experience of Writing Dissertation Works): Textbook*. Edited by D.O. Milko. Institute of Mechanization of Animal Husbandry of NAAS. Zaporizhzhia: STATUS. [in Ukrainian].
15. Aliiev, E.B. (2023). *Numerical Modeling of Processes in Agro-Industrial Production: Textbook*. Kyiv: Agrarna Nauka, 340 p. DOI: https://doi.org/10.31073/978-966-540-584-9 [in Ukrainian].

РЕЗУЛЬТАТИ ЕКСПЕРИМЕНТАЛЬНИХ ДОСЛІДЖЕНЬ МАШИНИ ДЛЯ ОЧИЩЕННЯ НАСІННЯ РИЦИНИ

У роботі розглянуто актуальну проблему підвищення ефективності післязбиральної обробки рицини (Ricinus communis), зокрема очищення її насіння. Рицина є цінною технічною культурою, насіння якої містить до 50 % олії, що широко застосовується у різних галузях. Попри зростаючий попит на рицинову олію, впровадженню цієї культури в агровиробництво перешкоджає відсутність ефективних технічних засобів для очищення насіння, які б враховували його специфічні фізико-механічні властивості. Існуючі зерноочисні машини недостатньо ефективні для обробки рицини, що зумовлює значні втрати посівного матеріалу та зниження виходу олії.

Метою дослідження є створення експериментального зразка машини для очищення насіння рицини та визначення раціональних режимних параметрів її роботи. У роботі представлено конструкцію та принцип дії дослідного стенду, що складається з вузла механічного відокремлення насіння, системи аеродинамічного очищення та системи керування з частотним перетворювачем. Для оцінки ефективності роботи машини проведено експериментальні дослідження, під час яких змінювалися такі параметри: відстань між дробильними конусами, частота їх обертання та швидкість повітряного потоку.

У результаті проведених експериментальних досліджень процесів відокремлення та очищення насіння рицини були встановлені залежності основних експлуатаційних показників розробленої машини – продуктивності Q, споживаної потужності P, питомих витрат енергії E, частки нерозлущених плодів ξ_f *та вмісту ліквідного насіння у забірнику* ψ_{s-s} *– від конструктивно-режимних параметрів: відстані між зворотнім і дробильним конусами δ, частоти обертання дробильного конусу n і швидкості повітряного потоку V. Проведений статистичний аналіз отриманих рівнянь регресії дозволив оцінити вплив кожного з досліджуваних факторів на результативні показники, виявити найбільш значущі параметри та побудувати адекватні математичні моделі. Оптимізацію параметрів проведено за допомогою методу скалярного ранжування з мінімізацією мультиплікативної цільової функції у середовищі Wolfram Cloud, що дало можливість визначити раціональні значення керувальних параметрів (δ = 10,8 мм; n = 563 об/хв; V = 3,6 м/с), які забезпечують найкраще поєднання енергетичної ефективності та технологічної якості процесу (E = 0,0394 МДж/кг; Q = 163,4 кг/год; P = 1861 Вт;* $\xi_f = 0{,}099$; $\psi_{s-s} = 0{,}958$*). Отримані результати свідчать про ефективність запропонованої конструкції та доцільність її подальшого впровадження у виробничі умови для очищення насіння рицини.*

Ключові слова: *рицина, очищення насіння, плоди, післязбиральна обробка, машинобудування, енергоефективність, дробильний конус, аеродинамічне очищення, експериментальні дослідження, регресійний аналіз, оптимізація параметрів, продуктивність, частота обертання, швидкість повітряного потоку.*

Ф. 7.Рис. 5. Літ. 15.

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