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# RESULTS OF LABORATORY STUDIES ON THE PHYSICO-MECHANICAL PROPERTIES OF CASTOR FRUITS AND SEEDS

**Elchyn ALIIEV,** Doctor of Technical Sciences, Senior Researcher, Professor
**Valentyn HOLOVCHENKO,** Recipient of the Third Educational and Scientific Level, Junior Research Associate
Dnipro State Agrarian and Economic University

**АЛІЄВ Ельчин Бахтияр огли,** д.т.н., старший дослідник, професор
**ГОЛОВЧЕНКО Валентин Володимирович**, здобувач третього освітньо-наукового рівня, молодший науковий співробітник
Дніпровський державний аграрно-економічний університет

*The aim of the study is to investigate the physicomechanical properties of castor fruits and seeds (Ricinus communis L.) to substantiate the design and technological parameters of machines and equipment intended for their extraction and cleaning.*

*Laboratory research on specialized equipment was conducted to determine the primary physical-mechanical properties of castor bean fruits and their components (segments, seeds, and capsule particles). These properties include geometric dimensions (length L and width B), mass M, bulk $\rho_b$ and true $\rho_d$ densities, angle of repose φ, friction coefficients (sliding μ' and static μ), and terminal velocity V. It was found that seeds exhibit the highest true density (567 ± 54 kg/m³) and the lowest friction coefficients, contributing to their superior flowability and mobility in technological processes. Fruits have the largest mass (1.18 ± 0.13 g) and terminal velocity (11.75 ± 1.43 m/s), influencing their cleaning and sorting methods. Capsule particles have the lowest density (101 ± 17 kg/m³) and terminal velocity (3.21 ± 0.51 m/s), allowing for effective separation using aerodynamic techniques. The results were applied in numerical modeling for a castor bean seed cleaning machine.*

*Rheological analysis of the compression behavior of castor bean fruits and seeds revealed a pronounced nonlinear dependence on time and absolute deformation. The deformation process of fruits involves multiple stages: an initial linear increase in force within elastic deformation, capsule cracking ($F_{f1}$ = 63.67 ± 3.52 N, $\Delta x_{f1}$ = 3.32 ± 0.75 mm), slowing of force growth in the plastic phase, a sharp drop during capsule rupture ($F_{f2}$ = 172.96 ± 9.55 N, $\Delta x_{f2}$ = 7.19 ± 0.79 mm), followed by a smooth increase in force during internal compression. A similar pattern is observed for seeds, but rupture ($F_{s2}$ = 48.91 ± 8.34 N, $\Delta x_{s2}$ = 2.4 ± 0.62 mm) is accompanied by a sharp force decrease without a distinct plastic deformation phase. Statistical analysis confirmed that the force and deformation distributions conform to the normal distribution law.*

***Key words**: castor bean, seed, fruit, physical-mechanical properties, geometric dimensions, rheology, compression, destruction, cleaning.*

***Fig. 6. Table. 2. Ref. 21.***

## 1. Problem formulation

According to the latest bioeconomy directives issued by the European Union, the industrial sector should rely more on bio-based materials instead of traditional petroleum resources [1, 2]. The agricultural sector can contribute to this goal by improving the utilization of processed products from oilseed crops [3, 4]. However, the cultivation of industrial crops raises concerns regarding land use and, consequently, competition between food and non-food crops [5]. The possibility of growing industrial crops on low-productivity lands may serve as the best compromise for achieving the EU’s future energy targets without reducing the land available for food production [6, 7]. Therefore, it is worth exploring value-added chains for crops with low resource requirements to address current challenges for their large-scale implementation.

In this context, castor *(Ricinus communis L.)* is a promising non-food crop [8, 9], which can be cultivated under low-resource conditions in Ukraine, achieving seed yields of 1.6–1.8 t/ha (variety Olesya), 1.7–2.1 t/ha (variety Khortychanka), and 1.5–1.7 t/ha (variety Khortytska 3) [10, 11]. Additionally, castor oil can be used for various applications, such as biodiesel production, cosmetics, pharmaceuticals, paints, varnishes, lubricants for two-stroke engines, or semi-rigid foam components for thermal insulation [12, 13].

Its contribution to reducing the dependence of the EU and Ukraine on vegetable oil imports for industrial and energy purposes could be significant if an efficient domestic supply chain for castor oil is properly developed. Ricinus communis L. is known for its many wild and semi-cultivated types, which differ in genetic and phenotypic characteristics, reaching heights similar to an average tree [14]. Castor seeds grow inside capsules arranged on one or more racemes, which develop gradually throughout the plant's life. As a result, seed ripening on racemes is non-uniform [15, 16]. This complicates the mechanization of castor seed harvesting, and the market still lacks specialized machinery. Therefore, seeds have to be harvested manually, increasing the production costs of castor oil and its related by-products. However, manual harvesting is feasible for high-reproduction seed material due to the small volumes involved [17]. Nevertheless, a technical challenge arises in extracting and cleaning castor seeds from the fruits (capsules).

## 2. Analysis of recent research and publications

However, despite the promising potential of castor (*Ricinus communis* L.), its industrial cultivation and processing face a number of technological challenges, the most significant of which is the lack of efficient equipment for mechanized seed extraction and cleaning. This is due to the specific physicomechanical properties of castor fruits and seeds, which differ significantly from those of other oilseed crops [18].

Currently, there is a lack of systematic research on the rheological and mechanical characteristics of castor seeds, such as shell strength, elasticity, resistance to deformation, and other parameters that influence the seed extraction process from capsules [19]. The absence of this data complicates the development of specialized equipment capable of efficiently and gently separating the seeds without damage.

Given this, an important scientific task is to study the physicomechanical properties of castor fruits and seeds to substantiate the design and technological parameters of machines for their cleaning. Conducting such research will contribute to the development of efficient mechanized harvesting and processing technologies for castor, which, in turn, will facilitate its large-scale implementation in production.

## 3. The purpose of the article

The aim of the study is to investigate the physicomechanical properties of castor fruits and seeds *(Ricinus communis L.)* to substantiate the design and technological parameters of machines and equipment intended for their extraction and cleaning.

## 4. Results and discussion

Laboratory studies of the physicomechanical properties of castor fruits of the «Khortychanka» variety and its components (segments (valves), seeds, and capsule particles) were carried out in several stages.

The determination of the moisture content of castor fruits and their components is carried out using the Radwag MA 110.R laboratory moisture meter, which operates on the gravimetric principle of drying the sample to a constant weight with automatic weight change control.

The determination of the geometric dimensions (length, width) of castor fruits and their components is carried out using the thickness gauge TP 25-100, while the mass is determined using the TBE-0.3 laboratory scale.

The determination of the bulk and true density of castor fruits and their components is an important parameter for their transportation and subsequent processing. The bulk density is determined using the method of filling a one-liter Pyrex PH-2 container, while the true density is calculated based on the mass and volume of the displaced liquid.

The determination of the angle of repose of castor fruits and their components is an important parameter for evaluating the flow properties of the material, which affects the processes of transportation and technological processing. Specialized equipment is used for measurement. The method for determining the angle of repose involves forming a cone of loose material by slowly and evenly pouring castor fruits or seeds through a funnel onto a horizontal surface until a natural bulk cone is formed.

The determination of the coefficients of sliding and static friction of castor fruits and seeds against the equipment wall was carried out using a device developed by Aliiev E.B. (Fig. 1) [20].

The determination of the falling velocity of castor fruits and their components was carried out in a special setup (Fig. 2), consisting of a cylindrical vertical aerodynamic tube, a fan for creating an airflow with an aerodynamic stabilizer (mesh), and a Benetech GM816 anemometer for measuring the air velocity.

The rheological properties of castor fruits and seeds were determined using a penetrometer developed by Aliiev E.B., Mykolenko S.Yu., and Dudyn V.Yu. [21]. The general appearance of the measurement process is shown in fig. 3.

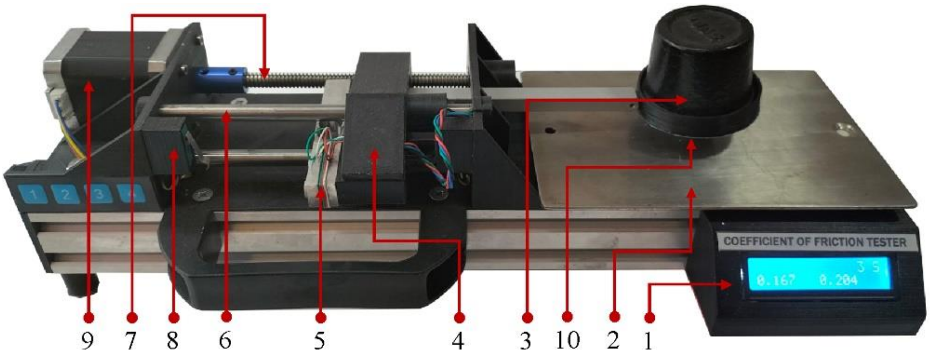


***Fig. 1. Determination of the coefficients of sliding and static friction of castor fruits and seeds against the equipment wall using a specialized device: 1 – control unit; 2 – workbench (steel or rubber); 3 – weight; 4 – carriage; 5 – strain gauge; 6 – guides; 7 – screw; 8 – limit switch; 9 – stepper motor; 10 – sample.***

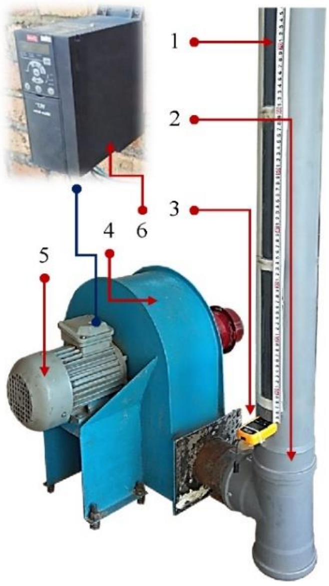


***Fig. 2. Determination of the falling velocity of castor fruits and their components using specialized equipment:***
***1 – vertical aerodynamic tube; 2 – aerodynamic stabilizer (mesh); 3 – Benetech GM816 anemometer; 4 – centrifugal fan; 5 – asynchronous three-phase electric motor; 6 – Danfoss Micro Drive FC51 frequency converter***

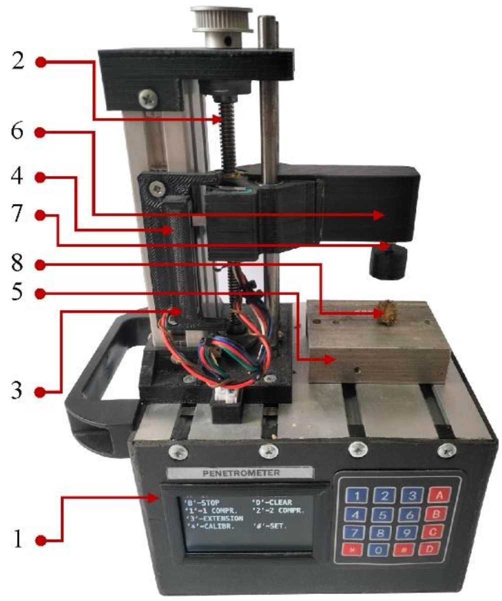


***Fig. 3. Study of the rheological properties of castor fruits and seeds using a penetrometer:***
***1 – control unit of the penetrometer; 2 – vertical displacement module; 3 – distance measurement module; 4 – limit switch module; 5 – workbench; 6 – strain gauge; 7 – cylindrical-shaped indenter; 8 – castor fruit or seed sample.***

The castor fruit is an oval-globular three-celled capsule, which can crack open, either bare or with spines, containing three seeds and having three valves. During the laboratory studies, the determination of the main physicomechanical properties of the fruit, segments (valves), seeds, and capsule particles was carried out, which were obtained as a result of the preliminary preparation of castor seed material. These properties were used for simulating the processes of seed separation and cleaning.

The first step was the separation of the components of the castor seed mixture into distinct groups (fruits, segments, seeds, capsule particles), which are shown in Fig. 4.

*Fruits*

*Segments (valves)*

*Seeds*

*Capsule particles*

***Fig. 4. Photos of the separate component groups of the castor seed mixture***

The moisture content of castor fruits and their components was on average 6.82±0.74%.

The summarized table of data and results of the statistical analysis of the determined physicomechanical properties of castor fruits and their components is presented in Table 4.1.

The results of the statistical processing of the variation series of the physicomechanical properties of castor fruits and their components show significant differences between their parameters.

Geometric characteristics (length L and width B) gradually decrease when moving from whole fruits to seeds, which is explained by the segmentation process of the fruits and the subsequent separation of the seeds from the shell. Fruits have the largest dimensions (L = 14.8 ± 2.2 mm, B = 13.5 ± 1.9 mm), while seeds are significantly smaller (L = 12.5 ± 1.8 mm, B = 7.1 ± 1.5 mm). The data confirm that the seeds have more stable dimensions, as the correlation coefficient (R) for their length and width is 0.84–0.90, indicating high homogeneity of the sample.

The mass of the studied objects also changes according to the structure of the fruits: the largest mass is observed in the fruits (1.18 ± 0.13 g), while the segments (0.34 ± 0.05 g) and seeds (0.29 ± 0.04 g) have significantly lower weights. High values of the correlation coefficient (R = 0.88–0.92) indicate the stability of this parameter.

The density of the fruits and their components changes depending on their structure. Bulk density (ρb) is highest for seeds (485 ± 48 kg/m³), while fruits have significantly lower values (264 ± 30 kg/m³), which is due to the presence of air cavities in the interior of the fruits. True density (ρd) is also highest in the seeds (567 ± 54 kg/m³), while for fruits, it is lower (434 ± 51 kg/m³), and lowest for capsule particles (248 ± 33 kg/m³), which is explained by their loose structure. These data confirm that seeds are the most dense component of castor, affecting their behavior during separation and cleaning.

The angle of repose (φ) indicates the flow properties of the materials. Fruits have φ = 33.8 ± 3°, while the segments are characterized by a higher value (37.7 ± 3.2°), indicating their lower flowability and greater tendency to stick together. This is explained by their irregular shape and the presence of shell residues, which increase internal friction.

Friction coefficients demonstrate significant variability between the studied components. Fruits have the highest sliding friction coefficient (μrub = 0.548 ± 0.056), which is explained by their rough surface and the presence of the shell. For seeds, this value is much lower (0.226 ± 0.026), indicating their smooth surface. Static friction (μst) also decreases from fruits (0.209 ± 0.028) to seeds (0.191 ± 0.017), confirming the improved mobility of the seeds during transportation and cleaning.

*Table 1.*

***Results of the statistical processing of the variation series distributions of the determined physicomechanical properties of castor fruits and their components***

| Property | Fruits | | | Segments (valves) | | | Seeds | | | Capsule particles | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Value | $\chi^2$ | R | Value | $\chi^2$ | R | Value | $\chi^2$ | R | Value | $\chi^2$ | R |
| L, mm | 14.8 ± 2.2 | 7.43 | 0.86 | 14.4 ± 1.6 | 13.96 | 0.82 | 12.5 ± 1.8 | 7.70 | 0.90 | – | – | – |
| B, mm | 13.5 ± 1.9 | 8.54 | 0.85 | 7.8 ± 1.7 | 9.32 | 0.84 | 7.1 ± 1.5 | 9.90 | 0.84 | – | – | – |
| M, g | 1.18 ± 0.13 | 8.77 | 0.91 | 0.34 ± 0.05 | 7.90 | 0.88 | 0.29 ± 0.04 | 8.03 | 0.92 | – | – | – |
| $\rho_b$, kg/m$^3$ | 264 ± 30 | 13.04 | 0.54 | 292 ± 24 | 11.64 | 0.75 | 485 ± 48 | 16.11 | 0.82 | 101 ± 17 | 9.16 | 0.81 |
| $\rho_d$, kg/m$^3$ | 434 ± 51 | 15.01 | 0.84 | 410 ± 39 | 10.62 | 0.89 | 567 ± 54 | 7.53 | 0.83 | 248 ± 33 | 8.92 | 0.89 |
| φ, ° | 33.8 ± 3 | 15.56 | 0.83 | 37.7 ± 3.2 | 10.29 | 0.80 | – | – | – | – | – | – |
| $\mu_{st}$ | 0.209 ± 0.028 | 14.01 | 0.89 | – | – | – | 0.191 ± 0.017 | 14.92 | 0.87 | – | – | – |
| $\mu_{rub}$ | 0.548 ± 0.056 | 8.38 | 0.83 | – | – | – | 0.226 ± 0.026 | 10.57 | 0.85 | – | – | – |
| $\mu`_{st}$ | 0.174 ± 0.015 | 10.01 | 0.85 | – | – | – | 0.141 ± 0.013 | 8.20 | 0.84 | – | – | – |
| $\mu`_{rub}$ | 0.207 ± 0.029 | 13.88 | 0.88 | – | – | – | 0.199 ± 0.017 | 7.32 | 0.79 | – | – | – |
| V, m/s | 11.75 ± 1.43 | 10.49 | 0.80 | 8.11 ± 1.14 | 7.70 | 0.80 | 8.65 ± 1.2 | 7.69 | 0.84 | 3.21 ± 0.51 | 12.74 | 0.86 |

The falling velocity (V) is an important parameter affecting seed separation. Fruits have the highest falling velocity (11.75 ± 1.43 m/s), which is related to their large mass and significant aerodynamic resistance. Segments and seeds have lower velocities (8.11 ± 1.14 m/s and 8.65 ± 1.2 m/s, respectively), which allows them to be efficiently separated from the fruits. The lowest value is observed in capsule particles (3.21 ± 0.51 m/s), confirming their low density and lightness.

Thus, the obtained data indicate regular changes in the physicomechanical characteristics of castor components, which can be explained by their morphological structure and structural features. The study of the rheological properties of castor fruits and seeds involved their sequential compression using a penetrometer. The number of samples (repetitions) for each group was 50. Examples of the obtained dependencies of the compressive force F (N) of the castor fruits and seeds on time t (s) or absolute deformation Δx (mm), considering the constant speed of the indenter (4 mm/s), are shown in Figs. 5-6.

The analysis of the force F versus time t dependence of castor bean fruits allows us to assess their mechanical properties, such as elasticity, plasticity, and failure point. At the initial stage of testing, the force F increases linearly, as the elastic deformation of the fruit shell occurs. At this point, the force-time relationship is approximately described by a linear function. As compression time increases, when the force reaches the value $F_{f1}(\Delta x_{f1})$, the shell cracks. After that, the fruit starts losing its elastic properties, the deformation becomes plastic, and the rate of force increase slows down. In this zone, the relationship can be described by a power or exponential function. Upon reaching the critical force $F_{f2}(\Delta x_{f2})$, the shell breaks, accompanied by a sharp drop in force. At this moment, a peak is observed in the F(t) graph, after which the load sharply decreases. Further compression occurs in the inner part of the fruit, namely the seed (not shown in Fig. 6), and the force-time relationship becomes linear again, but with a smaller slope, as the seed is less elastic than the shell. Therefore, the force compression dependence of castor bean fruits on time is nonlinear and includes several stages: initial linear increase, shell cracking, slowing down in the plastic deformation zone, a sharp drop upon shell rupture, and then a smooth increase during seed compression. Such an analysis allows us to evaluate the mechanical characteristics of the fruits, which is important for their pre-processing, sorting, and transportation.

The analysis of the force F versus time t dependence for castor bean seeds allows us to determine their mechanical properties, including elasticity, plasticity, and failure point. At the initial stage of testing, the force

F increases linearly, corresponding to the elastic deformation of the seed. During this period, the force-time relationship is approximately described by a linear function, as the seed resists compression, gradually accumulating stress. When the critical stress is accumulated (force $F_{s2}(\Delta x_{s2})$), seed failure occurs, and a sharp decrease in force is observed. After that, as the load increases, the seed begins to lose its elastic properties, and the force-time relationship transitions to a nonlinear regime, as plastic deformation occurs. At this moment, the seed shell material gradually changes its structure, which can be described by a power or exponential function. Thus, the force compression dependence of castor bean seeds on time includes several consecutive stages: initial linear force increase during elastic deformation, a sharp drop after shell failure, and further smooth force increase. Such analysis is essential for understanding the mechanical properties of castor bean seeds, which is significant for their processing, sorting, and transportation.

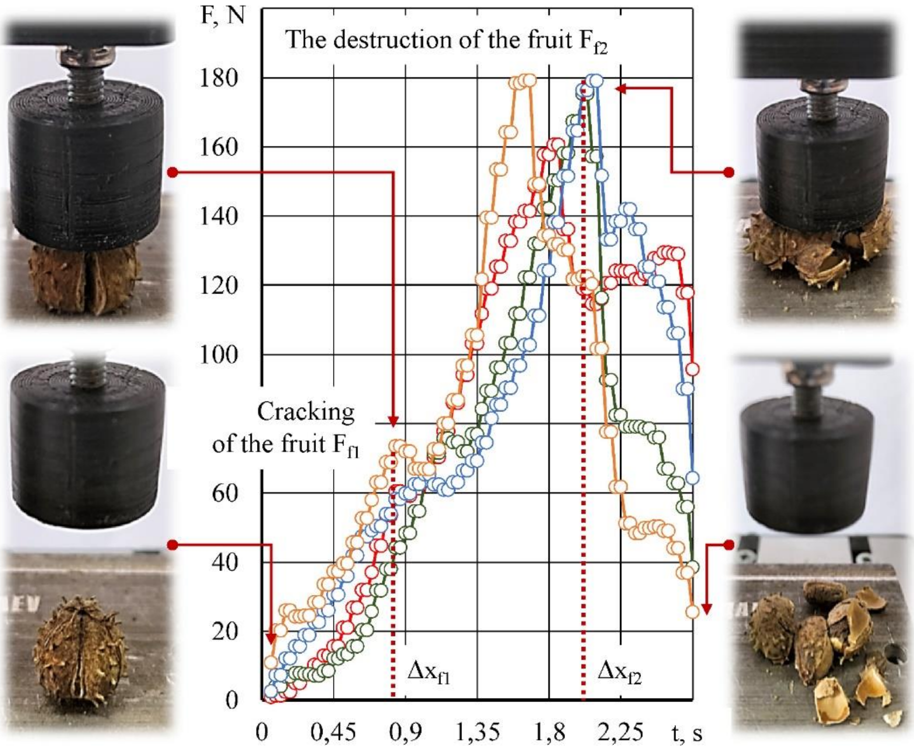


***Fig. 5. Examples of the dependence of the compressive force F of castor bean fruits on time t***

The summarized data on the statistical processing of the variation series are presented in Table 2.

***Table 2.***

***Results of statistical processing of the variation series of force and absolute deformation distributions at which cracking and destruction of castor bean fruits and seeds are observed***

| Property | $F_{f1}$, N | $\Delta x_{f1}$, mm | $F_{f2}$, N | $\Delta x_{f2}$, mm | $F_{s2}$, N | $\Delta x_s$, mm |
|---|---|---|---|---|---|---|
| Value | 63.67±3.52 | 3.32±0.75 | 172.96±9.55 | 7.19±0.79 | 48.91±8.34 | 2.4± 0.62 |
| $\chi^2$ | 7.6 | 14.5 | 13.2 | 8.0 | 9.7 | 7.8 |
| R | 0.929 | 0.870 | 0.860 | 0.855 | 0.787 | 0.796 |

The analysis of the results of statistical processing of the variation series of force and absolute deformation distributions, at which cracking and destruction of castor bean fruits and seeds are observed, shows a high agreement between the empirical data and the theoretical law of normal distribution. The mean values of the forces and deformations at which cracking and destruction occur have low standard deviations, indicating relatively low variability in the structural properties of the fruits and seeds of castor bean. The smallest destruction force is observed in the seeds ($F_{s2}$ = 48.91±8.34 N), confirming their weaker structure compared to the fruits ($F_{f2}$ = 172.96±9.55 N). The absolute deformation at destruction is also smallest in the seeds ($\Delta x_{s2}$ = 2.4±0.62 mm), indicating their lower ability to undergo plastic deformation compared to the fruits ($\Delta x_{f2}$ = 7.19±0.79 mm). The calculated values of the consistency criterion $\chi^2$ for all parameters (ranging from 7.6 to 14.5) are lower than the tabulated value $\chi_{tab2}$ = 16.9, confirming the conformity of the experimental distributions to the theoretical ones at the specified significance level (0.05). This indicates the absence of statistically significant deviations and the reliability of the obtained data. The correlation coefficients R for all parameters range from 0.787 to 0.929, indicating a strong relationship between force and the corresponding absolute deformation. The highest correlation is observed for the cracking force of the fruits (R = 0.929), indicating a high predictability of the behavior of the shell under load. The slightly lower correlation values for the destruction force of the seeds (R = 0.787) may be related to the greater heterogeneity of the internal structure of the seeds. Thus, the obtained results indicate the stability of the mechanical characteristics of castor bean fruits and seeds and allow for accurate prediction of their behavior under compression.

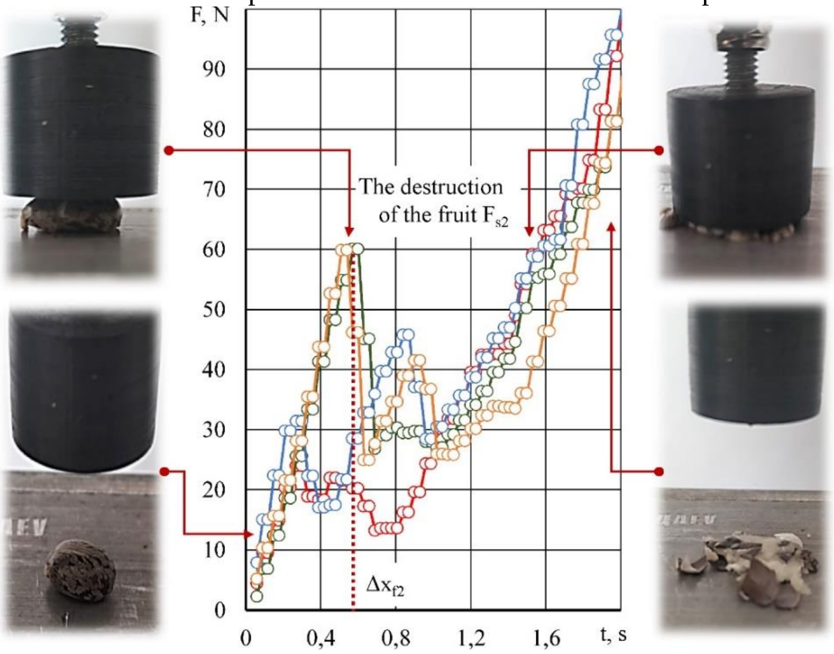


***Fig. 6. Examples of the dependence of the compressive force F of castor bean fruits on time t***

The high correlation between force and deformation, as well as the confirmation of the distribution consistency according to the $\chi^2$ criterion, indicate the possibility of using these characteristics for further optimization of processing and sorting technological processes.

## 5. Conclusion

As a result of laboratory research on specialized equipment, the main physical-mechanical properties of castor bean fruits and their components (segments, seeds, and capsule particles) were established, including geometric dimensions (length L and width B), mass M, bulk $\rho_b$ and true $\rho_d$ density, angle of repose φ, friction coefficients (sliding μ' and static μ), and terminal velocity V. It was found that the seeds have the highest true density (567 ± 54 kg/m³) and the lowest friction coefficients, which provide better flowability and mobility in technological processes. The fruits have the largest mass (1.18 ± 0.13 g) and terminal velocity (11.75 ± 1.43 m/s), which affect their cleaning and sorting methods. Capsule particles have the lowest density (101 ± 17 kg/m³) and the lowest terminal velocity (3.21 ± 0.51 m/s), which allows them to be effectively separated using aerodynamic methods. The obtained results were used during numerical modeling of a machine for cleaning castor bean seeds.

The study of the rheological properties of castor bean fruits and seeds showed that their mechanical behavior during compression exhibits a pronounced nonlinear dependence on time and absolute deformation. Analysis of the obtained compression force F dependencies on time t (absolute deformation Δx) indicates that the deformation process of castor bean fruits involves several consecutive stages: initial linear increase in force within the elastic deformation range, moment of capsule cracking ($F_{f1}$ = 63.67 ± 3.52 N, $\Delta x_{f1}$ = 3.32 ± 0.75 mm), slowing of force growth in the plastic deformation phase, sharp drop during capsule rupture ($F_{f2}$ = 172.96 ± 9.55 N, $\Delta x_{f2}$ = 7.19 ± 0.79 mm), and subsequent smooth increase in force during compression of the internal part of the fruit. A similar deformation pattern is observed for castor bean seeds, but the moment of rupture ($F_{s2}$ = 48.91 ± 8.34 N, $\Delta x_{s2}$ = 2.4 ± 0.62 mm) is accompanied by a sharp decrease in force without a distinct plastic deformation stage. Statistical processing of experimental data confirmed the conformity of the force and deformation distributions to the normal distribution law.

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## РЕЗУЛЬТАТИ ЛАБОРАТОРНИХ ДОСЛІДЖЕНЬ ФІЗИКО-МЕХАНІЧНИХ ВЛАСТИВОСТЕЙ ПЛОДІВ І НАСІННЯ РИЦИНИ

*Метою дослідження є вивчення фізико-механічних властивостей плодів і насіння рицини (Ricinus communis L.) для обґрунтування розрахункових і технологічних параметрів машин і обладнання, призначених для їхнього видобутку та очищення.*

*Лабораторні дослідження на спеціалізованому обладнанні були проведені для визначення основних фізико-механічних властивостей плодів рицини та їх компонентів (сегментів, насіння та частинок коробочки). Ці властивості включають геометричні розміри (довжина L і ширина B), масу M, насипну $\rho_b$ і дійсну $\rho_d$ щільність, кут природного укосу $\varphi$, коефіцієнти тертя (ковзання $\mu'$ і спокою $\mu$), а також швидкість витання V. Встановлено, що насіння має найвищу дійсну щільність (567 ± 54 кг/м³) та найнижчі коефіцієнти тертя, що забезпечує йому кращу сипучість і рухливість у технологічних процесах. Плоди мають найбільшу масу (1,18 ± 0,13 г) та швидкість витання (11,75 ± 1,43 м/с), що впливає на методи їх очищення та сортування. Частинки коробочки мають найменшу щільність (101 ± 17 кг/м³) і найнижчу швидкість витання (3,21 ± 0,51 м/с), що дозволяє ефективно їх відокремлювати за допомогою аеродинамічних методів. Отримані результати будуть використані під час чисельного моделювання машини для очищення насіння рицини.*

*Реологічний аналіз поведінки плодів і насіння рицини під час стиснення показав виражену нелінійну залежність від часу та абсолютної деформації. Процес деформації плодів включає кілька етапів: початкове лінійне зростання сили в межах пружної деформації, момент розтріскування оболонки ($F_{f1}$ = 63,67 ± 3,52 Н, $\Delta x_{f1}$ = 3,32 ± 0,75 мм), уповільнення росту сили в фазі пластичної деформації, різкий спад при руйнуванні оболонки ($F_{f2}$ = 172,96 ± 9,55 Н, $\Delta x_{f2}$ = 7,19 ± 0,79 мм), і подальше плавне зростання сили під час стискання внутрішньої частини плоду. Подібний характер деформації спостерігається й для насіння, однак момент руйнування ($F_{s2}$ = 48,91 ± 8,34 Н, $\Delta x_{s2}$ = 2,4 ± 0,62 мм) супроводжується різким зниженням сили без вираженої стадії пластичної деформації. Статистичний аналіз підтвердив, що розподіли сил і деформацій відповідають закону нормального розподілу.*

***Ключові слова:*** *рицина, насіння, плід, фізик-механічні властивості, геометричні розміри, реологія, стиснення, руйнування, очищення.*

***Рис. 6. Табл. 2. Літ. 21.***

### *INFORMATION ABOUT THE AUTHORS*

**Elchyn ALIIEV** – Doctor of Technical Sciences, Senior Researcher, Professor of the Departments of Mechanization of Production Processes in Animal Husbandry of Dnipro State Agrarian and Economic University (St. S. Efremova, 25, Dnipro, Ukraine, 49000, e-mail: aliev@meta.ua, https://orcid.org/0000-0003-4006-8803).
**Valentyn HOLOVCHENKO –** Recipient of the Third Educational and Scientific Level, Junior Research Associate of the Department of Technical Systems Engineering of Dnipro State Agrarian and Economic University (St. S. Efremova, 25, Dnipro, Ukraine, 49000, e-mail: golovchenkov@i.ua, https://orcid.org/0009-0007-9719-126X).

**АЛІЄВ Ельчин Бахтияр огли** – доктор технічних наук, старший дослідник, професор кафедри інжинірингу технічних систем Дніпровського державного аграрно-економічного університету (вул. Сергія Єфремова, 25, м. Дніпро, Україна, 49000, e-mail: aliev@meta.ua, https://orcid.org/0000-0003-4006-8803).
**ГОЛОВЧЕНКО Валентин Володимирович** – здобувач третього освітньо-наукового рівня, молодший науковий співробітник Дніпровського державного аграрно-економічного університету (м. Дніпро, вул. Сергія Єфремова, 25, e-mail: golovchenkov@i.ua, https://orcid.org/0009-0007-9719-126X).