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VERIFICATION OF THE RHEOLOGICAL MODEL OF FRACTURE OF CASTOR FRUITS AND SEEDS BASED ON EXPERIMENTAL DATA

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The paper presents a comprehensive study of the mechanical behavior of castor fruits and seeds under static compression by combining laboratory testing with numerical analysis in a discrete element environment. The aim was to determine the consistency between calculated results and experimental data and to assess the accuracy of reproducing the crack initiation and fracture processes of the biological material. During the experiments, the limiting forces and absolute deformations corresponding to the onset of cracking and complete failure of the samples were determined. For fruits, the maximum force was 172.96 ± 9.55 N at a deformation of 7.19 ± 0.79 mm, while for seeds it was 48.91 ± 8.34 N at a deformation of 2.4 ± 0.62 mm. The obtained variation series correspond to the normal distribution law (χ^2 = 7.6–14.5 < 16.9 at p = 0.05) and show high correlation coefficients between force and deformation (R = 0.787–0.929), indicating the statistical reliability of the results. The numerical model incorporated the physical and mechanical properties of the material, including Young's modulus, Poisson's ratio, ultimate stresses, and cohesive energy. The simulation reproduced three loading stages: elastic deformation, local shell damage, and final fracture followed by fragment compaction. The discrepancy between the calculated and experimental peak force values did not exceed 5–10%, confirming the adequacy of the selected parameters and the correctness of modeling contact interactions. It was established that the seeds are characterized by lower strength and a lower capacity for plastic deformation compared to the fruits, due to the peculiarities of their internal structure. The obtained results can be used to predict material behavior in technological processes such as cleaning, transportation, and processing, as well as to optimize the design and operating parameters of equipment with consideration of energy efficiency and reduction of raw material damage.

Keywords: compression, strength, ultimate force, deformation, discrete element method, contact interaction

Introduction. Improving the efficiency of castor seed processing and cleaning requires a thorough study of its physical, mechanical, and rheological properties (Wu et al., 2025; Hou et al., 2019). Castor fruits and seeds, as biological objects, possess a complex multicomponent structure that combines elastic, plastic, and brittle elements; therefore, their behavior under compressive loading is characterized by nonlinearity and a multistage fracture process (Cárdenas Pérez et al., 2014; Chakrabarty et al., 2021). Insufficient consideration of these features in the design of technological equipment leads to reduced cleaning quality, excessive energy consumption, and seed damage.

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Modern approaches to analyzing the mechanical behavior of plant raw materials are based on a combination of experimental methods and numerical modeling (Wiącek et al., 2012). Laboratory studies make it possible to determine critical force and deformation values, establish "force–deformation" relationships, and assess the statistical variability of strength parameters (Yang et al., 2021; Dudin et al., 2024). At the same time, numerical modeling, particularly using the discrete element method (DEM), enables the reproduction of internal fracture mechanisms, analysis of particle contact interactions, and prediction of material behavior under various loading conditions (Bilous et al., 2025).

Verification of rheological fracture models based on experimental data is of particular importance, since the correctness of model parameters determines their suitability for engineering calculations and optimization of structural and technological equipment parameters. The agreement between laboratory test results and numerical simulations confirms the adequacy of the adopted assumptions regarding the mechanism of shell and fruit fracture, load distribution patterns, and the transition from elastic to brittle-plastic deformation stages (Kharchenko et al., 2025; Chen et al., 2023).

In contemporary studies of the mechanical properties of biological materials, both experimental methods for determining rheological parameters and numerical modeling are widely applied. For example, the discrete element method (DEM) has been used to simulate shell breakage and particle contact interactions in plant materials, followed by comparison with physical experiments (Looh et al., 2025). Reviews of DEM and coupled DEM models (e.g., with CFD or FEM) in agricultural processes cover more than one hundred studies addressing grain mechanics, fruits, and soils (Maraveas et al., 2025).

A number of studies focus on the mechanical properties of specific seed materials. For instance, the dependence of physical and mechanical characteristics of seeds on moisture content has been investigated, including fracture force and deformation under different moisture conditions (Ramaj et al., 2024). These experimental studies demonstrated a significant effect of moisture on seed mechanical behavior, which is essential for assessing their rheological properties. Similarly, experimental measurements of the mechanical parameters of castor seeds have been conducted to determine ultimate forces, Young's modulus, and fracture energy used in the design of oil extraction equipment (Yang et al., 2021).

Regarding fracture and contact modeling, advanced particle interaction models (e.g., Hertz–Mindlin) are commonly applied, enabling more accurate prediction of mechanical behavior under bending, compression, and tension (Fan et al., 2025; Bilous et al., 2025). Such combined modeling approaches have been successfully used to verify DEM parameters through laboratory experiments for various biomaterials, including plant stems and leaves (Gu et al., 2025).

Experimental literature also includes studies on the rheological parameters of dispersed and organic materials, describing methods for measuring elasticity, plasticity, and stress response during pressing and deformation (Qingqiu et al., 2024; Yang et al., 2025; Liu et al., 2023). The results of these works provide a foundation for correctly determining the physical and mechanical constants required for DEM model calibration.

Thus, numerous studies address similar problems in various crops and materials, confirming the relevance of combining laboratory research and numerical

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modeling as an effective approach to studying the rheology and mechanical characteristics of biological objects such as castor fruits and seeds.

The aim of this study is to verify a rheological model of fracture of castor fruits and seeds by comparing laboratory experimental results with numerical simulation data and to assess their degree of agreement for further application in the design and optimization of seed processing machinery.

Materials and Methods. To develop a rheological model of castor fruits and seeds, a combined approach integrating laboratory experiments and numerical modeling was applied.

Laboratory measurements of rheological properties were carried out on fruits of the Khortytska variety (Vedmedeva et al., 2018). All experiments were conducted under controlled environmental conditions, with an air temperature of 20.4 ± 2.1°C and relative humidity of 53.4 ± 5.2%.

The average moisture content of the fruits and seeds was 6.82 ± 0.74%. The dimensions of castor fruits were L_f = 14.8 ± 2.2 mm and B_f = 13.5 ± 1.9 mm, while the seeds measured L_s = 12.5 ± 1.8 mm and B_s = 7.1 ± 1.5 mm. The average mass of the fruits was 1.18 ± 0.13 g, whereas the seeds were significantly lighter at 0.29 ± 0.04 g.

The rheological properties of fruits and seeds were determined using a penetrometer (Aliiev et al., 2022). The operating principle of the device is as follows: a fruit or seed is placed on a working platform beneath a cylindrical indenter with a diameter of 20 mm, mounted on a load cell capable of vertical movement. Before each measurement, the load cell with the indenter is calibrated so that the force reading equals zero in the resting state (Fig. 1). The indenter then moves downward at a constant speed. The moment of first contact between the indenter and the sample is recorded as the start of measurement. During the experiment, the dependence of compressive force F (N) and absolute deformation Δx (mm) on time t (s) is recorded. The measurement accuracy is 0.1 N for force and 0.01 mm for deformation.

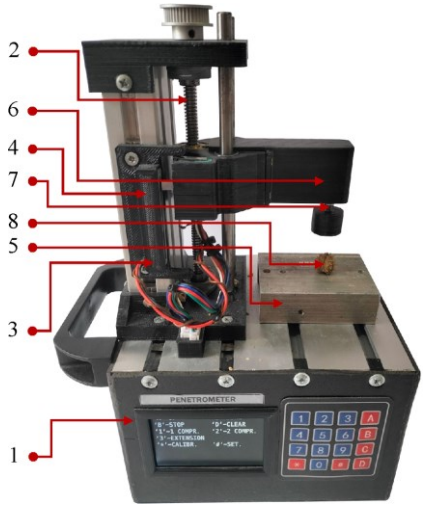

Fig. 1. **Investigation of the rheological properties of castor fruits and seeds using a penetrometer**

Notes: 1 – penetrometer control unit; 2 – vertical movement module; 3 – displacement measurement module; 4 – limit switch module; 5 – working platform; 6 – load cell; 7 – cylindrical indenter; 8 – fruit or seed sample of castor

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To study the mechanical destruction processes of castor fruits and seeds under compressive loading, it is advisable to use the discrete element method (DEM) in combination with a set of physical models implemented in the Simcenter Star-CCM+ environment. The structure of castor fruits is multiphase, consisting of a hard shell and soft seeds (Fig. 2), while under loading, pronounced contact and fragmentation behavior is observed, making a meshless modeling approach in a Lagrangian framework most relevant. Meshless DEM allows modeling the behavior of a large number of bodies as particles without the need to construct a classical finite element mesh, where each particle, whether a seed or a fruit fragment, is treated as a separate body with individual physical and mechanical properties. This approach is particularly effective for simulating destruction, as the structure changes dynamically: particles may collide, separate, or disappear due to fragmentation, allowing accurate reproduction of the fruit shell cracking process.

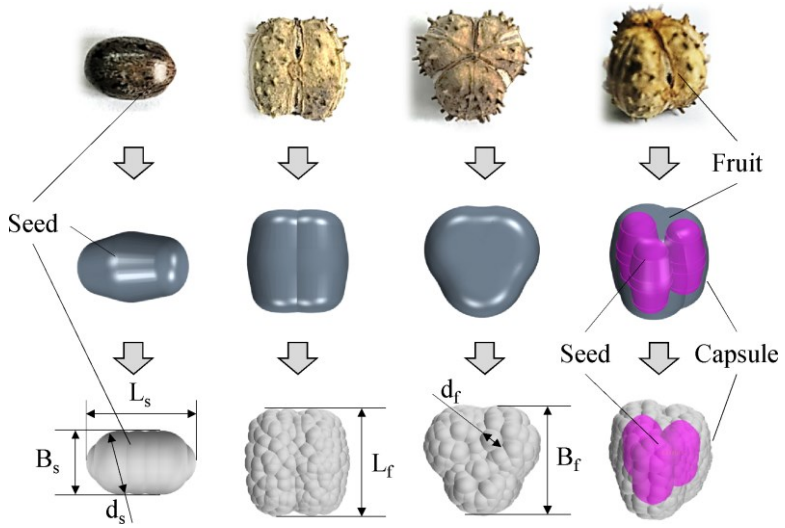

Fig. 2. **Study of the rheological properties of castor fruits and seeds using a penetrometer**

Notes: L_f, L_s – length of castor fruits and seeds; B_f, B_s – width of castor fruits and seeds; d_f, d_s – diameters of the sub-particles of the castor fruit and seed models

Source: developed by the author

The interaction between particles, as well as between particles and rigid walls such as the indenter or piston, is described using contact force models that account for elasticity, friction, damping, and cohesion. For the castor shell, elastic models, such as linear Hookean elasticity, and visco-plastic models are employed to describe the material's resistance to deformation and subsequent shear. Since DEM operates in a Lagrangian coordinate system, interpolation of parameters from the computational grid is required to correctly transfer loads from the continuum to the seed particles.

Modeling the multiphase structure involves separate descriptions of the physical and mechanical properties of the shell and the seed core, limiting particle lifetimes in the computational domain, maintaining constant material density, and representing particle behavior in clusters, which reflects real agglomeration and adhesion after destruction. Phase interactions are implemented through single-fracture models that define critical loads or deformations; when these thresholds are exceeded,

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a particle fragments, producing a set of smaller fragments with corresponding impulse transfer. Additionally, rolling resistance, initial cohesive adhesion of shell particles, and inter-phase force transmission during deformation are considered, ensuring accurate modeling of gradual fracture and shell–seed content interactions.

The DEM methodology allows consideration of all particle contact interactions, including normal and tangential forces, rolling moments, and cohesion, as well as specification of contact parameters, particle geometry, and fracture criteria. Calculations are performed in a transient mode with an implicit integration scheme, ensuring stability even at high fracture velocities and a large number of contacts. Inclusion of gravitational force enables realistic particle arrangement before compression and accurate particle kinematics during fragment fall and residue compaction. The chosen model complex in Simcenter Star-CCM+ provides high physical fidelity for simulating the fracture of castor fruits and seeds, reproducing key phenomena such as fragmentation, loss of contacts, particle adhesion, and fragment transport. This methodology allows prediction of mechanical strength, fracture behavior, and material comminution efficiency, which is practically important for oil extraction technologies.

The schematic of the compression-based fracture modeling process for castor fruits and seeds is shown in Fig. 3.

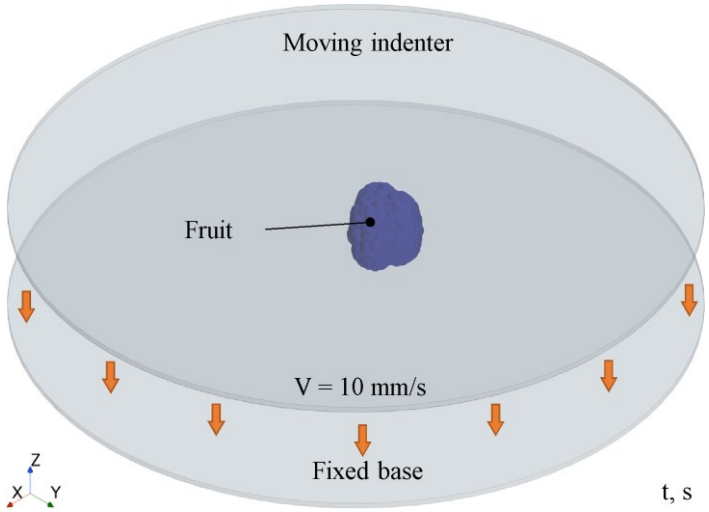

Fig. 3. **Schematic of the compression-based fracture modeling process of castor fruits and seeds**

Source: developed by the author

The physicomechanical properties of castor fruit and seeds adopted for modeling, based on the data from the previous study, include the main dimensions, elastic moduli, and other mechanical characteristics, and additionally account for rheological properties. Specifically, the diameter of the fruit constituent particles is 14 mm, while that of the seeds is 8 mm. The Poisson's ratio is 0.36 for the fruit and 0.24 for the seeds. The Young's modulus is set at 85 MPa for the fruit and 210 MPa for the seeds. The specific cohesion energy per unit volume Ω is 1200 J/m³ for the fruit and 4500 J/m³ for the seeds. The ultimate tensile and shear stress W is 1.8 MPa for the fruit and 6.5 MPa for the seeds. These parameters were used to configure the discrete

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element model, ensuring an accurate reproduction of the mechanical behavior of castor fruits and seeds under compressive loads.

Results and Discussion. The rheological properties of castor fruits and seeds were investigated by sequential compression using a penetrometer, with 50 samples tested for each group. Examples of the dependence of compressive force F (N) of fruits and seeds on time t (s) or absolute deformation Δx (mm) at a constant indenter movement speed of 4 mm/s are shown in Fig. 4.

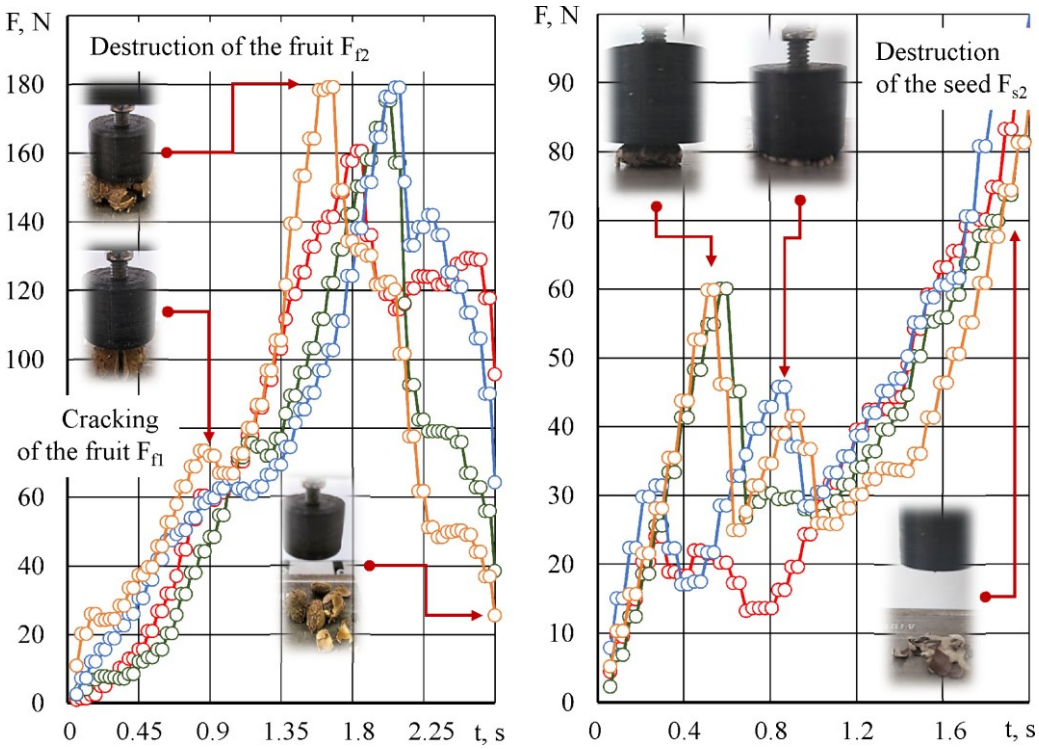

Fig. 4. **Examples of the dependence of compressive force F of castor fruits and seeds on time t based on laboratory test results**

Source: developed by the author

The analysis of these dependencies allows for the assessment of the mechanical properties of castor fruits, specifically elasticity, plasticity, and fracture limits. At the initial stage of testing, the force F increases linearly, corresponding to the elastic deformation of the fruit shell, and the force–time relationship can be approximated by a linear function. As the compression time increases and the force reaches $F_{f1}(\Delta x_{f1})$, the fruit shell begins to crack, after which the fruit loses its elastic properties, and deformation transitions into plastic behavior. This is reflected in a slower increase in force, which can be described by a power or exponential function. When the critical force $F_{f2}(\Delta x_{f2})$ is reached, the shell fails, accompanied by a sharp drop in force and the formation of a peak on the F(t) graph. Further compression of the inner part of the fruit, the seed, is characterized by a repeated linear increase in force, but with a smaller slope, as the seed exhibits lower elasticity compared to the shell. Thus, the compressive force–time relationship of castor fruits is nonlinear and includes several sequential stages: initial linear growth, shell cracking, slowed force increase

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during plastic deformation, sharp drop during shell failure, and subsequent smooth increase during seed compression. Analyzing these features allows for the evaluation of the mechanical characteristics of the fruits, which is important for processing, sorting, and transportation.

A similar analysis of the compressive force of castor seeds as a function of time t allows for the determination of their elastic and plastic properties, as well as the point of failure. At the initial stage of testing, the force F rises linearly, corresponding to the elastic deformation of the seed, and the force–time relationship can be approximated by a linear function, as the material accumulates stress under compressive loading. When the force reaches the critical value $F_{s2}(\Delta x_{s2})$, seed rupture occurs, accompanied by a sharp drop in force F. Further loading leads to plastic deformation of the seed, manifested as a nonlinear force–time relationship that can be approximated by a power or exponential function. Thus, the compressive force–time dependence of castor seeds includes several stages: initial linear growth during elastic deformation, a sharp drop after shell failure, and a subsequent smooth increase in force, which is important for evaluating the mechanical properties of seeds during processing, sorting, and transportation.

Histograms of the distributions of F_{f1}, Δx_{f1}, F_{f2}, Δx_{f2}, F_{s2}, Δx_{s2} and the corresponding normal distribution curves are shown in Fig. 5.

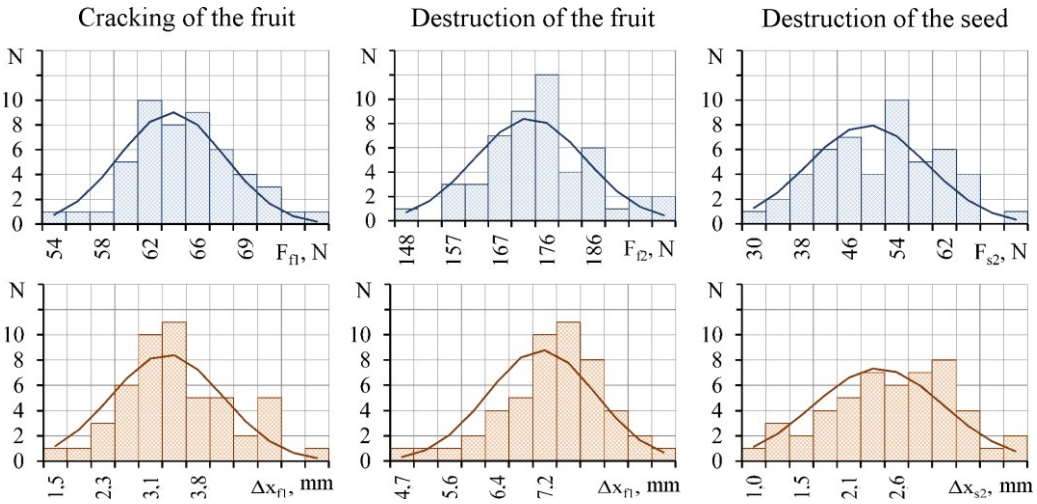

Fig. 4. **Distributions of forces and absolute deformations at which cracking and failure of castor fruits and seeds are observed**

Source: developed by the author

Analysis of the statistical processing results of the variation series, reflecting the distributions of forces and absolute deformations at which castor fruits and seeds crack and fail, showed a high agreement of empirical data with the theoretical normal distribution law. The mean values of forces and deformations corresponding to the moment of cracking and failure are characterized by low standard deviations, indicating relatively low variability in the structural properties of the fruits and seeds. The lowest failure forces are observed in the seeds ($F_{s2} = 48.91 \pm 8.34$ N), confirming their lower strength compared to fruits ($F_{f2} = 172.96 \pm 9.55$ N). Absolute deformation

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at failure is also smallest for the seeds (Δx_{s2} = 2.4 ± 0.62 mm), indicating a limited capacity for plastic deformation compared to the fruits (Δx_{f2} = 7.19 ± 0.79 mm).

The calculated χ^2 goodness-of-fit values for all parameters (ranging from 7.6 to 14.5) are below the tabulated value χ^2_{tab} = 16.9, confirming that the experimental distributions match theoretical expectations at a significance level of 0.05, with no statistically significant deviations and a high level of reliability of the obtained data. Correlation coefficients R for all parameters vary from 0.787 to 0.929, indicating a strong relationship between force and corresponding absolute deformation. The highest correlation is observed for the fruit cracking force (R = 0.929), indicating high predictability of the shell's behavior under load, whereas slightly lower correlation values for the seed failure force (R = 0.787) may be explained by greater heterogeneity in its internal structure.

Thus, the obtained results confirm the stability of the mechanical characteristics of castor fruits and seeds and allow for reliable prediction of their behavior under compression. The high correlation between force and deformation, along with the confirmation of distribution agreement by the χ^2 criterion, indicates that these characteristics can be used for further optimization of processing and seed-sorting technologies.

The process of castor fruit failure under compressive loading, according to numerical modeling results, exhibits a complex multiphase nature (Fig. 5).

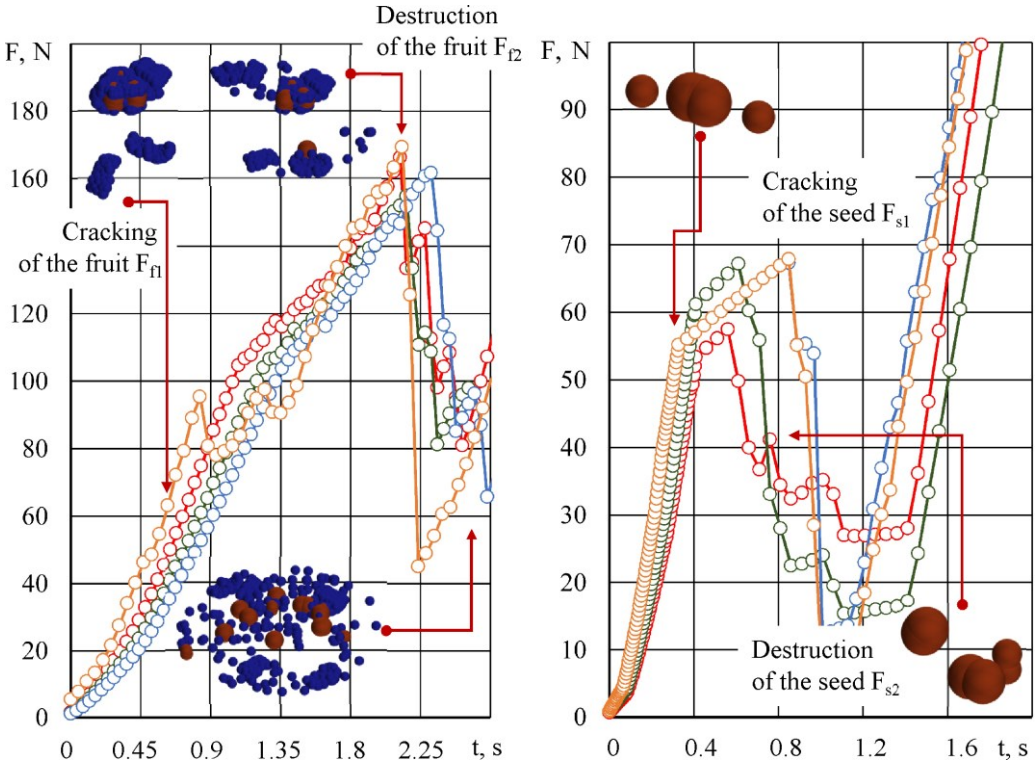

Fig. 4. **Examples of compressive force F dependencies of castor fruits and seeds on time t according to numerical modeling results**

Source: developed by the author

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At the initial stage (up to ~0.5 s), a gradual increase in force from 0 to approximately 49 N is observed, corresponding to the elastic deformation of the outer shell of the castor fruit. During this period, the fruit structure resists deformation without visible damage, accumulating elastic energy. In the interval 0.4–0.9 s, the compressive force rises rapidly, and at ~66 N local shell integrity violations and the onset of its destruction occur. Between 0.9–1.0 s, a force plateau is observed, reflecting gradual destruction of the internal core and redistribution of the load among the remaining intact parts. Then, in the range 1.0–2.1 s, the force sharply increases to a maximum value of ~170 N, corresponding to the culmination phase of failure, when the outer shell and internal components completely lose structural integrity and transform into separate particles. After this, over a short interval (~0.1 s), a sharp drop in force to 45 N occurs, indicating complete fruit failure. The subsequent increase in force to ~110 N in the interval 2.2–3.0 s is associated with compaction and additional compression of the fragments. The final phase (after 3.0 s) is characterized by a decrease in force, indicating saturation of the deformation process due to the absence of structural integrity. Thus, fruit failure can be divided into three main stages: elastic deformation, shell and core destruction, and compaction of the residues after failure, with load distribution shifting from the outer shell to the inner soft tissues. The magnitude and duration of the load peaks depend on the fruit's geometry and the mechanical properties of the shell, pulp, and presence of voids. Numerical modeling results provide a deeper understanding of the mechanism of gradual failure of the biological object and are used to calibrate discrete element method (DEM) models in Simcenter Star-CCM+.

The process of castor seed failure under compressive loading, according to numerical modeling, is characterized by continuous force growth up to a critical point, followed by a sharp decrease in resistance, which is typical behavior for biological materials (Fig. 4). At the initial stage (0–0.4 s), an almost linear increase in force from 0 to ~58 N is observed, corresponding to elastic deformation of the seed coat. By 0.41–0.46 s, the force reaches ~58 N, after which temporary stabilization or slowing of the increase occurs, indicating the onset of local failure—microcracks or partial splitting of the seed coat. In the interval 0.46–0.61 s, the compressive force increases more slowly, reaching a local maximum of about 67 N, after which a sharp drop occurs: 60 N at 0.66 s and 55 N at 0.71 s, corresponding to the active phase of seed failure. In the range 0.76–1.06 s, the force significantly decreases from 42 N to 19 N, reflecting loss of structural integrity and movement of internal fragments. Starting from 1.11 s, the force gradually increases again due to compaction and further compression of the crushed residues, and from 1.41 s, the rate of force increase sharply rises, reaching a new maximum of about 89.6 N at 1.81 s, caused by additional resistance of the compacted fragments or remaining solid part of the core.

Physically, the seed failure process includes several stages: elastic deformation, onset of failure, destruction of outer and inner structures with force drop, mechanical compaction and fragmentation of residues, and the final attainment of a new maximum in the already fully destroyed structure. Comparison of numerical modeling with laboratory results shows identical dependency patterns (Figs. 3 and 5), confirming the applicability of numerical modeling for substantiating the design and technological parameters of machines for cleaning and processing castor seeds.

Thus, the comparison of laboratory and numerical modeling results of castor fruit and seed failure demonstrates high consistency between them (Table 1): critical failure forces, deformation magnitudes, time to reach peak loads, and the nature of the

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F(t) and F(Δx) curves practically coincide in both laboratory and model. Laboratory studies provide accurate empirical values of the mechanical characteristics of fruits and seeds, while numerical modeling allows detailed analysis of the internal dynamics of failure, load distribution in the multiphase structure, and the influence of various parameters (Young's modulus, friction coefficient, shell elasticity). The combination of both approaches not only confirms the empirical data but also allows prediction of the behavior of castor fruits and seeds under compression in real technological processes, which is practically important for optimizing the design and technological parameters of processing and sorting equipment.

Table 1

Comparison of Laboratory Results and Numerical Modeling of Castor Fruit and Seed

Parameter	Laboratory Data – Fruit	DEM Modeling – Fruit	Laboratory Data – Seed	DEM Modeling – Seed
Initial cracking, force F_1, N	63.67±3.52	~66	61.23±3.46	~56
Initial cracking, deformation Δx_1, mm	3.32±0.75	~3.9	1.8± 0.54	~1.9
Complete failure, force F_2, N	172.96±9.55	~170	48.91±8.34	~42
Complete failure, deformation Δx_2, mm	7.19±0.79	~7.8	2.4± 0.62	~2.5

Source: developed by the author

Comparison of laboratory results and numerical modeling showed a high degree of agreement between the data, confirming the effectiveness of the combined approach for studying the rheological properties of castor fruits and seeds. Laboratory measurements provided accurate empirical values of critical failure forces, deformation magnitudes, and the time to reach peak loads, while numerical modeling enabled a detailed analysis of the internal failure mechanisms, stress distribution in the multiphase structure, and the influence of the material's physicomechanical parameters (Hou et al., 2019; Wu et al., 2025).

Analysis of the force–deformation and force–time curves, F(Δx) and F(t), revealed that fruit and seed failure occurs in multiple stages: initial linear force increase corresponding to elastic deformation of the shell, local failure of the outer shell and inner components, and compaction of fragments after failure. This behavior reflects the complex structure of biological objects, combining elastic, plastic, and brittle elements, and confirms the high relevance of multiphase models in DEM simulations (Cárdenas Pérez et al., 2014; Chakrabarty et al., 2021).

Verification of the DEM model using laboratory measurements allowed refinement of particle interaction parameters, including the modulus of elasticity, friction coefficient, cohesion magnitude, and failure criteria. Comparison of F(t) and F(Δx) curves showed that the modeling accurately reproduces the three main stages of failure: elastic deformation, active shell and core rupture, and subsequent fragment compaction. Such agreement confirms the applicability of the DEM model for predicting the mechanical behavior of castor fruits and seeds in real technological

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processes, such as sorting, transportation, and oil extraction (Bilous et al., 2025; Chen et al., 2023).

Literature analysis indicates that the combination of laboratory methods and numerical modeling is widely used in studies of the mechanical properties of biomaterials (Wiącek et al., 2012; Looh et al., 2025; Maraveas et al., 2025). For example, in cereal crops and other oilseeds, DEM modeling allows consideration of particle contact interactions, phase heterogeneity, and the effect of moisture on failure force and deformation (Ramaj et al., 2024). The combined approach increases prediction accuracy, reduces energy overuse and seed damage, and optimizes the design and operational parameters of equipment (Fan et al., 2025; Gu et al., 2025; Liu et al., 2023).

Thus, the conducted study confirms the feasibility of an integrated approach combining laboratory measurements and numerical modeling for investigating the rheology and mechanical behavior of castor fruits and seeds. The demonstrated high agreement of the data indicates that the verified DEM model can serve as a reliable tool for engineering design and optimization of technological processes for seed processing and cleaning (Qingqiu et al., 2024; Yang et al., 2025).

Conclusions. During the experimental studies, the critical forces and absolute deformations for the failure of castor fruits and seeds were determined: for the fruits, the failure force was 172.96 ± 9.55 N at a deformation of 7.19 ± 0.79 mm, while for the seeds, it was 48.91 ± 8.34 N at a deformation of 2.4 ± 0.62 mm. It was found that the seeds exhibit lower mechanical strength and reduced capacity for plastic deformation compared to the fruits. Statistical analysis of the results showed that the empirical distributions conform to the normal law (χ^2 = 7.6–14.5 < χ^2_{tab} = 16.9 at a significance level of 0.05) and revealed a high correlation between force and deformation (R = 0.787–0.929), confirming the reliability of the obtained data.

Numerical modeling reproduced the characteristic stages of failure–elastic deformation, local cracking, and final rupture with subsequent compaction of fragments and demonstrated a high agreement with laboratory results (peak value deviations did not exceed 5–10%). This indicates the adequacy of the adopted rheological parameters (Young's modulus, Poisson's ratio, critical stresses, cohesion energy) and the correct implementation of the model in the discrete element environment.

Thus, it was confirmed that the verified rheological model is a reliable tool for predicting the mechanical behavior of castor fruits and seeds under compression. The obtained results can be used to optimize the design and operational parameters of equipment for cleaning, crushing, and processing the seeds to reduce energy consumption and minimize material damage.

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ВЕРИФІКАЦІЯ РЕОЛОГІЧНОЇ МОДЕЛІ РУЙНУВАННЯ ПЛОДІВ І НАСІННЯ РИЦИНИ НА ОСНОВІ ЕКСПЕРИМЕНТАЛЬНИХ ДАНИХ

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У роботі представлено комплексне дослідження механічної поведінки плодів і насіння рицини при статичному стисканні з поєднанням лабораторних випробувань та чисельного аналізу в середовищі дискретних елементів. Метою було встановлення відповідності розрахункових результатів експериментальним показникам і оцінювання точності відтворення процесу тріщиноутворення та руйнування біологічного матеріалу. У ході експериментів визначено граничні сили та абсолютні деформації, що відповідають початку розтріскування й повному руйнуванню зразків. Для плодів максимальна сила становила 172,96 ± 9,55 Н при деформації 7,19 ± 0,79 мм, для насіння — 48,91 ± 8,34 Н при деформації 2,4 ± 0,62 мм. Отримані варіаційні ряди характеризуються відповідністю нормальному закону розподілу (χ^2 = 7,6–14,5 < 16,9 при p = 0,05) та високими коефіцієнтами кореляції між силою і деформацією (R = 0,787–0,929), що свідчить про статистичну надійність результатів. Чисельна модель враховувала фізико-механічні параметри матеріалу, зокрема модуль пружності, коефіцієнт Пуассона, граничні напруження та когезійну енергію.

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Моделювання відтворило три стадії навантаження: пружну деформацію, локальне пошкодження оболонки та остаточне руйнування з ущільненням уламків. Розбіжність між розрахунковими і експериментальними піковими значеннями сили не перевищувала 5–10%, що підтверджує адекватність прийнятих параметрів і коректність моделювання контактних взаємодій. Встановлено, що насіння характеризується меншою міцністю та меншою здатністю до пластичної деформації порівняно з плодами, що обумовлено особливостями їхньої внутрішньої структури. Отримані результати можуть бути використані для прогнозування поведінки матеріалу в технологічних процесах очищення, транспортування та переробки, а також для оптимізації конструктивних і режимних параметрів обладнання з урахуванням енергоефективності та зниження пошкоджуваності сировини.

Ключові слова: стиск, міцність, гранична сила, деформація, метод дискретних елементів, контактна взаємодія

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