CONTRIBUTIONS TO THE INVESTIGATION OF THE MECHANICAL BEHAVIOUR OF ROSE HIP SEEDS UNDER COMPRESSION AND CREEP TESTS: EXPLORATORY UNSUPERVISED CLASSIFICATION OF COMPRESSION RESPONSES
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CONTRIBUŢII LA CERCETAREA COMPORTAMENTULUI MECANIC AL SEMINŢELOR DE MĂCEŞE PRIN TESTE DE COMPRESIUNE ŞI FLUAJ: CLASIFICAREA EXPLORATORIE PRIN TEHNICI DE ÎNVĂŢARE AUTOMATĂ NESUPRAVEGHEATĂ A RĂSPUNSURILOR LA COMPRESIUNE

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ABSTRACT

This study proposes an artificial intelligence-based method for the automatic identification of natural groups of mechanical behaviour in rose hip seeds (Rosa canina). The method combines compression testing with unsupervised machine learning techniques, namely Principal Component Analysis (PCA) and K-means clustering, while creep tests are analysed separately to assess the time-dependent mechanical behaviour of the seeds. This approach enables the identification of distinct mechanical patterns and the objective classification of samples according to their response to mechanical loading. The unsupervised multivariate analysis was performed using mechanical features extracted from compression tests conducted on 25 individual rose hip seeds (n = 25), with each individual compression test generating a force–displacement dataset comprising 934 experimental data points. Each cluster was analysed separately in terms of the experimentally determined mechanical parameters. For each group, the mean values of maximum compression force (F_{max}), displacement at maximum force (x_{max}), deformation energy, and initial stiffness were calculated. The results revealed the existence of two main categories of mechanical behaviour. The first group was characterized by an average maximum force of approximately 141 N and a displacement at maximum force of 0.73 mm, indicating seeds with high mechanical strength. The second group exhibited an average maximum force of approximately 75 N and a displacement at maximum force of 0.85 mm, corresponding to seeds that were more deformable and less resistant to compression. The seeds were tested at a moisture content of 2.79% (wet basis), determined thermo-gravimetrically. To validate cluster separation and reduce the dimensionality of the dataset, Principal Component Analysis (PCA) was applied. The quality of clustering was assessed using the silhouette index, which indicated a satisfactory separation of samples according to their mechanical response. PCA revealed that the main differences between clusters were associated with maximum force, absorbed energy, and initial stiffness values, confirming the existence of distinct categories of mechanical behaviour within the analysed seed batch.

REZUMAT

Lucrarea de fata propune o metodă bazată pe inteligența artificială pentru identificarea automată a unor categorii distincte de comportament mecanic al semințelor de măceș (Rosa canina). Metoda integrează încercările de compresiune cu tehnici de învățare automată nesupravegheată, respectiv Analiza Componentelor Principale (PCA) și algoritmul K-means, în timp ce testele de fluaj sunt analizate separat pentru caracterizarea răspunsului mecanic al semințelor în timp. Această abordare permite evidențierea și clasificarea obiectivă a diferitelor tipuri de răspuns mecanic la compresiune. Analiza multivariată nesupravegheată a fost realizată utilizând caracteristici mecanice extrase din testele de compresiune efectuate pe 25 de semințe individuale de măceș (n = 25), fiecare test individual de compresiune generând un set de date forță–deplasare alcătuit din 934 de puncte experimentale. Fiecare cluster a fost analizat separat din punctul de vedere al parametrilor mecanici determinați experimental. Pentru fiecare grup au fost calculate valorile medii ale forței maxime de compresiune (F_{max}), deplasării la forța maximă (x_{max}), energiei de deformare și rigidității inițiale. Rezultatele au evidențiat existența a două categorii principale de comportament mecanic. Primul grup a fost *caracterizat printr-o forță maximă medie de aproximativ 141 N și o deplasare la forța maximă de 0,73 mm, indicând semințe cu rezistență mecanică ridicată. Al doilea grup a prezentat o forță maximă medie de aproximativ 75 N și o deplasare la forța maximă de 0,85 mm, corespunzând unor semințe mai deformabile și cu o rezistență mai redusă la compresiune. Semințele au fost testate la un conținut de umiditate de 2,79% (bază umedă), determinat prin metoda termogravimetrică. Pentru validarea separării clusterelor și reducerea dimensionalității setului de date a fost aplicată Analiza Componentelor Principale (PCA). Calitatea grupării a fost evaluată utilizând indicele silhouette, care a indicat o separare satisfăcătoare a probelor în funcție de răspunsul lor mecanic. Analiza PCA a evidențiat faptul că principalele diferențe dintre clustere au fost asociate cu valorile forței maxime, energiei absorbite și rigidității inițiale, confirmând existența unor categorii distincte de comportament mecanic în cadrul lotului de semințe analizat.*

INTRODUCTION

The need to identify and utilize new food resources with high nutritional and energy value, together with the continuous growth of the global population, has led to a significant increase in research efforts in this field worldwide. All available food resources can contribute, to a greater or lesser extent, to ensuring food security and meeting the nutritional requirements of the population. However, the efficiency of their utilization depends on their nutritional characteristics, availability, and the sustainability of production and valorisation processes (*Chen and Kates, 1994*) .

By combining state-of-the-art computational algorithms with the ability of modern computer systems to rapidly process very large volumes of data, researchers are now able to efficiently identify and evaluate solutions to complex problems whose direct experimental investigation may be costly, difficult, or time-consuming. In this way, optimized technical solutions can be obtained, capable of reproducing the behaviour of real physical phenomena with a high degree of accuracy within a reasonable time frame.

In this context, rose hip seeds (*Rosa canina*), derived from a perennial plant that is resistant to low temperatures, grows optimally in sunny or slightly shaded areas, and requires moderate irrigation, are of particular interest due to their nutritional and functional value (*Yildiz and Alpaslan, 2012*). The plant is characterized by delicate pale pink flowers followed by intensely red fruits (as shown in Fig. 1), which are well known for their high content of bioactive compounds, particularly vitamin C, polyphenols, and antioxidants (*Marmol et al., 2017*). Beyond its mechanical and technological relevance, *Rosa canina* has attracted considerable scientific interest due to the valuable chemical composition and diverse biological properties of its fruits and other plant components. *Demir and Özcan (2001)* highlighted the chemical and technological properties of wild rose fruits, while *Polumackanycz et al. (2020)* reported the rich phenolic composition and associated biological properties of dog rose fruits and leaves. The broader potential of *Rosa canina* has also been addressed through pharmacognostic investigations (*Oproshanska et al., 2021*) and through its use as a phytogenic source in animal nutrition (*Stătescu et al., 2025*). Collectively, these studies emphasize the considerable biological, nutritional, and technological value of *Rosa canina* and support continued research aimed at improving the characterization and valorisation of this plant and its derived materials.

a) b)

Fig. 1 – Rosa hip (rosa canina), wild: a) fruits; b) seeds

The mechanical behaviour and fracture resistance of agricultural seeds under compressive loading have been extensively investigated because of their relevance to handling, processing, grinding, and size-reduction operations. *Paulsen, (1978),* investigated the fracture resistance of soybeans subjected to compressive loading, while *Gupta and Das, (2000),* analysed the fracture resistance of sunflower seeds and kernels under compression.

Similar investigations were subsequently conducted by *Łysiak (2007),* who characterized the fracture toughness of pea seeds using Weibull analysis, and by *Khodabakhshian et al., (2010)*, who evaluated the mechanical properties of sunflower seeds and kernels under compressive loading. In addition to the intrinsic mechanical properties of the biological material, experimental factors such as moisture content, seed dimensions, loading rate, and loading orientation can substantially influence the force and energy associated with seed fracture, as investigated for cumin seeds by *Saiedirad et al., (2008).* The importance of specimen orientation and moisture level was also addressed by *Dowd et al., (2019),* in their study of cottonseed fracture resistance. These studies demonstrate that the mechanical response of seeds is strongly dependent on both material characteristics and testing conditions, emphasizing the importance of controlling moisture content, loading orientation, and compression conditions when evaluating fracture behaviour.

Ionescu et al., (2025), investigated the influence of grinding time on the particle size distribution of rose hip powder, highlighting its direct implications for various applications in the food and pharmaceutical industries. The authors emphasized that improvements in solubility, stability, and bioavailability form the basis for the development of new rose hip powder-based products tailored to the specific requirements of different industrial sectors. In addition, *Gokduman (2026)* conducted a comprehensive study on the main physical and mechanical characteristics of rose hip fruits, analysing parameters such as dimensions, mass, firmness, and the mechanical behaviour of the fruits under detachment and puncture loading conditions. Indentation techniques have also been extensively employed for the mechanical characterization of materials, with *Evans et al. (2013)* investigating nano-indentation methods for compliant materials and *Han et al. (2015)* analysing the factors influencing micro-indentation measurements.

The application of machine learning techniques for the characterization of elastic, viscoelastic, stress relaxation, and creep behaviour of agri-food materials has been addressed in numerous recent studies, including those conducted by *Xu (2020)*, *Biswas et al. (2020)*, *Li et al. (2021)*, and *Singh et al. (2026)*.

These studies propose and validate various predictive models based on machine learning algorithms that are capable of accurately estimating the characteristic parameters of creep and stress-relaxation phenomena. Their findings contribute to a deeper understanding and improved modelling of the rheological behaviour of agri-food materials.

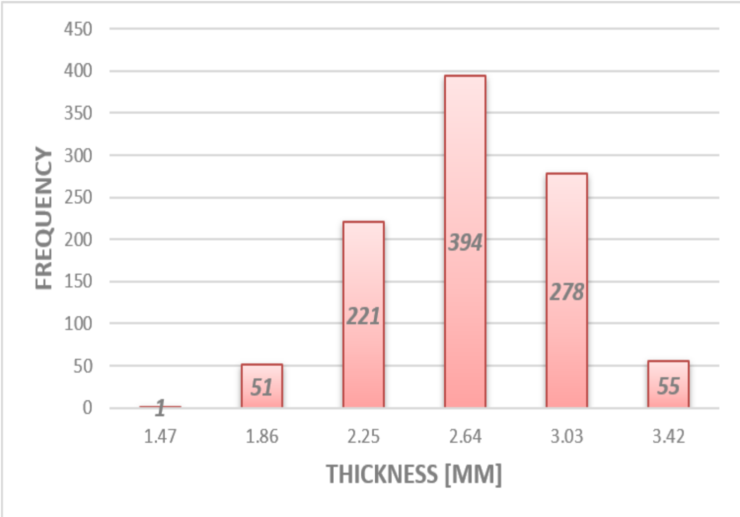
The main objective of the present study is the theoretical and experimental investigation of the mechanical behaviour of rose hip seeds subjected to compression and creep tests, as well as the identification of natural groups of mechanical response using unsupervised machine learning techniques. Mechanical features extracted from the force–displacement curves were analysed using Principal Component Analysis (PCA) and the K-means clustering algorithm in order to reveal distinct patterns of mechanical behaviour. The proposed approach enables an objective characterization of the mechanical response of the seeds and provides relevant insights into the mechanisms of deformation, energy absorption, and structural failure.

MATERIAL AND METHOD

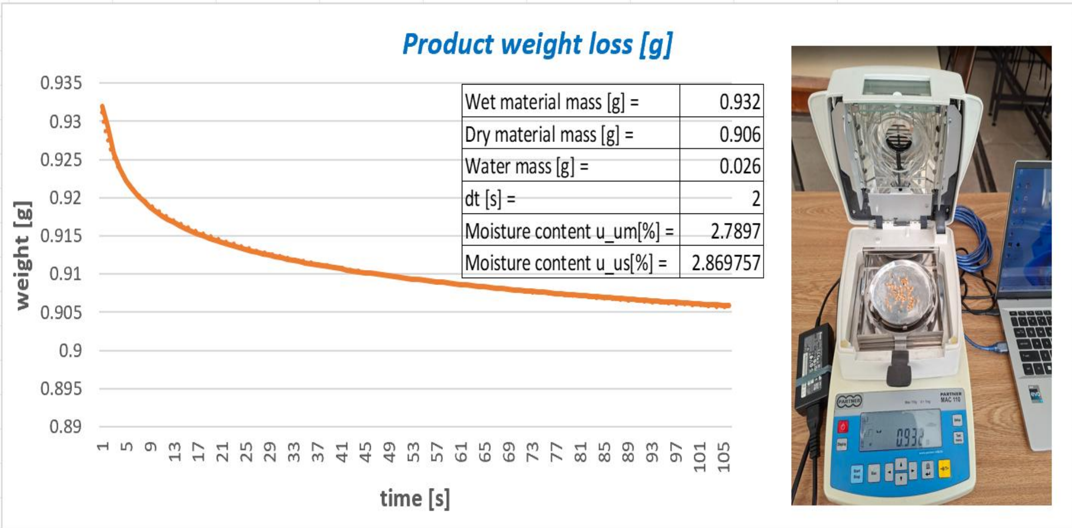
Rose hip seeds (*Rosa canina* L.) used in the experiments were obtained from mature fruits and cleaned prior to testing. The seeds were recovered after separation of the fruit pulp and subsequently dried until hygroscopic equilibrium was reached. Before mechanical testing, they were stored in plastic containers under laboratory conditions at a temperature of 22 ± 2 °C and a relative humidity of approximately 30%.

For the dimensional characterization of the experimental batch, 1,000 seeds were analysed and their thickness distribution was determined. The results revealed an approximately normal distribution, with most seeds exhibiting thickness values between 2.25 and 3.03 mm. The physical characterization of the rose hip seeds also included the determination of the thousand-seed weight (TSW), which was found to be 19.64 g. Together with the dimensional distribution presented in Figure 2a, this parameter indicates a relatively high degree of uniformity of the experimental batch used for the compression and creep tests. Seed dimensions were measured using a digital micrometre (measuring range: 0–25 mm, resolution: 0.001 mm, accuracy: ±0.001 mm; PR China). Seed mass was determined using the precision balance integrated into the PARTNER MAC 110 moisture analyser (RADWAG, Poland), with a maximum capacity of 110 g and a resolution of 1 mg. The same instrument was subsequently used for the thermo-gravimetric determination of seed moisture content. The moisture content of the rose hip seeds was determined thermo-gravimetrically using a PARTNER MAC 110 moisture analyser. The initial sample mass was 0.932 g and the final dry mass was 0.906 g, corresponding to a water loss of 0.026 g. The resulting moisture content was 2.79% on a wet basis, equivalent to 2.87% on a dry basis (Fig. 2b).

A unimodal distribution can be observed, with the highest frequency recorded for a thickness of 2.64 mm, corresponding to 394 seeds (39.4% of the total). An additional 278 seeds (27.8%) exhibited a thickness of approximately 3.03 mm, while 221 seeds (22.1%) had a thickness of approximately 2.25 mm. The results show that more than 89% of the analysed seeds had thickness values ranging from 2.25 to 3.03 mm, indicating a high degree of dimensional uniformity within the experimental batch. The small number of seeds with extreme thickness values, approximately 1.47 mm and 3.42 mm, suggests limited data dispersion and the absence of a significant number of outliers.



a)



b)

Fig. 2 – Physical characterization of rose hip (*Rosa canina L.*) seeds

(a) thickness distribution illustrating the dimensional uniformity of the experimental batch (N = 1000);
(b) thermo-gravimetric determination of seed moisture content using the PARTNER MAC 110 moisture analyser

Mechanical tests were performed using a Hounsfield 1K universal testing machine, equipped with a load cell appropriate for the investigated force range (0–1000 N) and controlled through QMat 5.50 software. Mechanical compression tests were performed using a Hounsfield 1K universal testing machine (Hounsfield Test Equipment Ltd., UK), equipped with a 1000 N load cell with a force measurement accuracy of 0.01 N and controlled through QMat 5.50 software. A crosshead speed of 15 mm/min was used for all specimens. Since this loading rate is higher than that commonly employed for strictly quasi-static testing of agricultural biological materials, its potential influence on the measured force–deformation response should be considered when interpreting the results. The experiments were carried out using a cylindrical indenter with a radius of 1.4 mm. Compression tests were conducted on 25 seeds randomly selected from the analysed population. Each specimen was tested only once, and the force–deformation data were continuously recorded throughout the loading process.

Stiffness was determined by calculating the slope of the linear portion of the force–deformation curve, while the fracture energy was calculated as the area under the curve up to the failure point. Similar mechanical evaluation procedures based on force–deformation curves have been reported for small fruits and other biological materials. (*Gageanu et al., 2021, Gökduman, 2026*).

Compression tests were performed at a crosshead speed of 15 mm/min. For each of the 25 compression tests, representative mechanical features were extracted from the force–displacement curve, including maximum compression force, displacement at maximum force, deformation energy, initial stiffness, mean force, RMS force, fracture index, and number of force peaks (*Stryjecka et al., 2024*). These variables were standardized using z-score normalization and subsequently analysed using Principal Component Analysis (PCA) and K-means clustering.

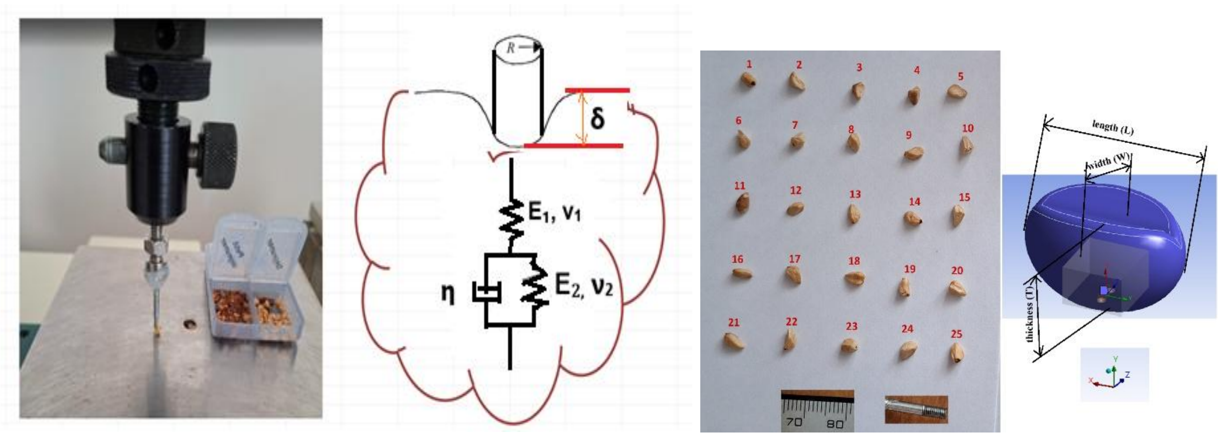
Creep tests were carried out by applying a constant load of 25 N for a period of 600 s. The evolution of deformation over time was continuously monitored, allowing the viscoelastic behaviour of the rose hip seeds to be evaluated. Data obtained from the creep tests were not included in the PCA or K-means analysis.

For the description of the creep behaviour of rose hip seeds, the Zener Standard Linear Solid (SLS) viscoelastic model, shown in Fig. 3, was employed. This model consists of an elastic element with modulus E_1, connected in series with a Kelvin–Voigt element composed of an elastic spring with modulus E_2 and a viscous dashpot characterized by the viscosity coefficient η. The Zener model is widely used to describe the viscoelastic behaviour of biological materials because it simultaneously represents the instantaneous elastic response and the time-dependent deformation. Within the model, the parameter E_1 characterizes the instantaneous elastic stiffness of the material, E_2 describes the delayed elastic component associated with relaxation and creep phenomena, while η represents the internal viscous resistance to deformation.

Data Analysis and Machine Learning.

Representative mechanical features were extracted from the force–displacement curves, including the maximum compression force, displacement at maximum force, deformation energy, initial stiffness, and the viscoelastic parameters determined using the Zener model (Fig. 3b).

To identify natural groups of mechanical behaviour, an unsupervised machine learning approach was employed. Dimensionality reduction of the dataset was performed using Principal Component Analysis (PCA), while sample clustering was carried out using the K-means algorithm. Figures 3c present the 25 seeds used for compression testing. The principal geometrical dimensions of the rose hip seed are defined in Figure 3d as length (L), width (W), and thickness (T). In the present experimental campaign, thickness was the dimension systematically measured and used for the dimensional characterization of the seed batch.



a) b) c) d)

Fig. 3 – Experimental system used for the mechanical characterization of rose hip seeds

(a) force sensor of the Hounsfield 1K universal testing machine employed for compression tests; (b) Standard Linear Solid (SLS) viscoelastic model, also known as the Zener model, used to describe the viscoelastic behaviour of the seeds; (c) rose hip seeds used in the compression tests (n = 25); (d) schematic representation of the principal seed dimensions: length (L), width (W), and thickness (T)

Before applying Principal Component Analysis (PCA), all mechanical features were standardized using the z-score normalization method in order to eliminate the influence of differences in scale among the variables. The normalization was performed according to the following equation:

$$z_{ij} = \frac{x_{ij} - \mu_j}{\sigma_j} \quad (1)$$

where x_{ij} is the original value of the variable, μ_j is the mean value of the variable, and σ_j is its standard deviation. The quality of the obtained clusters was evaluated using the silhouette index, calculated according to the following equation:

$$s(i) = \frac{b(i) - a(i)}{max[a(i), b(i)]} \tag{2}$$

where $a(i)$ represents the average distance between sample i and all other samples within the same cluster, while $b(i)$ represents the smallest average distance between sample i and the samples belonging to a different cluster.

The silhouette index ranges from −1 to 1. Values close to 1 indicate very good cluster separation, values close to 0 suggest overlap between clusters, whereas negative values indicate a possible misclassification of samples. In the present study, silhouette analysis was used to determine the optimal number of clusters and to evaluate the performance of the K-means algorithm.

RESULTS

The mechanical properties of rose hip seeds are essential for evaluating their behaviour during grinding processes and for optimizing powder production technologies. Similar mechanical assessments focused on compression, fracture, and fragmentation processes have also been reported for various medicinal and aromatic plants. In these studies, parameters such as maximum compression force, deformation energy, and stiffness have been identified as important indicators for the design and optimization of grinding and mechanical processing equipment for plant materials (*Yilmaz and Gökduman, 2015; Stan et al., 2014*).

Figure 4 shows the force–displacement curves obtained from compression tests performed on individual rose hip seeds. During the compression tests, the load was applied in the vertical direction, along the Y-axis, as illustrated in Figure 3d. The same loading configuration was maintained for all tested seeds.

A significant variability in the mechanical response can be observed, as evidenced by differences in the maximum force, displacement at failure, and overall curve shape. Some specimens exhibit a progressive increase in force followed by a sudden drop, associated with the fracture of the internal structure, whereas others display a more deformable behaviour characterized by gradual force increases and multiple successive fracture events. In some cases, the maximum force values exceed 200 N, indicating substantial differences in mechanical strength among the analysed seeds.

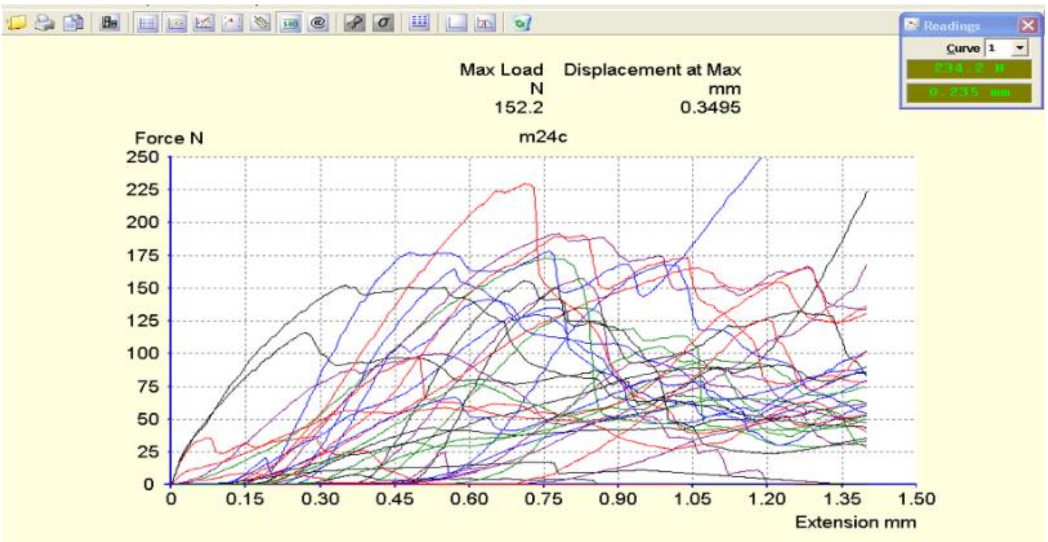
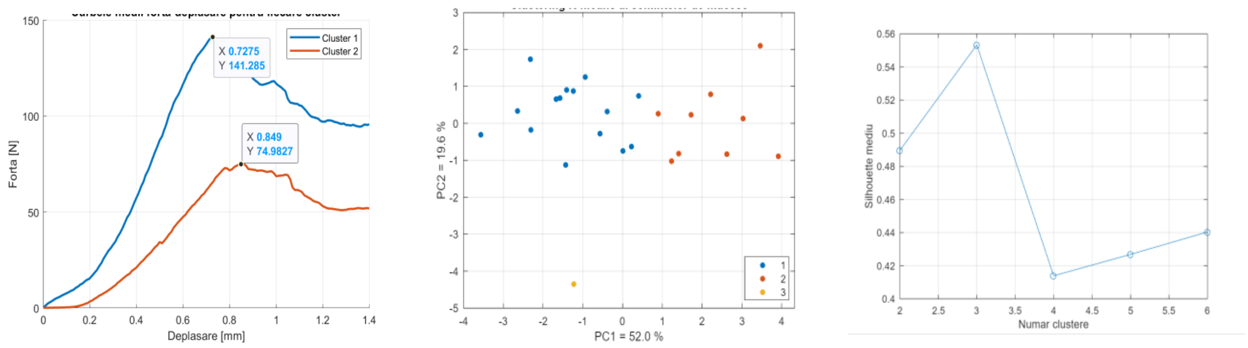


Fig. 4 – Force–displacement curves of rose hip seeds obtained from compression tests

In the absence of predefined classes, the force–displacement curves were analysed using unsupervised machine learning techniques to identify natural groups of mechanical behaviour among the rose hip seeds. Representative mechanical features were extracted from each force–displacement curve, including maximum force, displacement at maximum force, deformation energy, initial stiffness, mean force, RMS value, fracture index, and number of peaks. The data were standardized and analysed using Principal Component Analysis (PCA), while sample clustering was performed using the K-means algorithm.

Cluster analysis revealed the existence of two main categories of mechanical behaviour, shown in Fig. 5. Cluster analysis revealed two principal categories of compression behaviour. Cluster 1 was characterized by higher maximum force and deformation energy, indicating greater mechanical resistance. Cluster 2 exhibited lower maximum force and energy values and greater deformability, corresponding to a mechanically less resistant response.



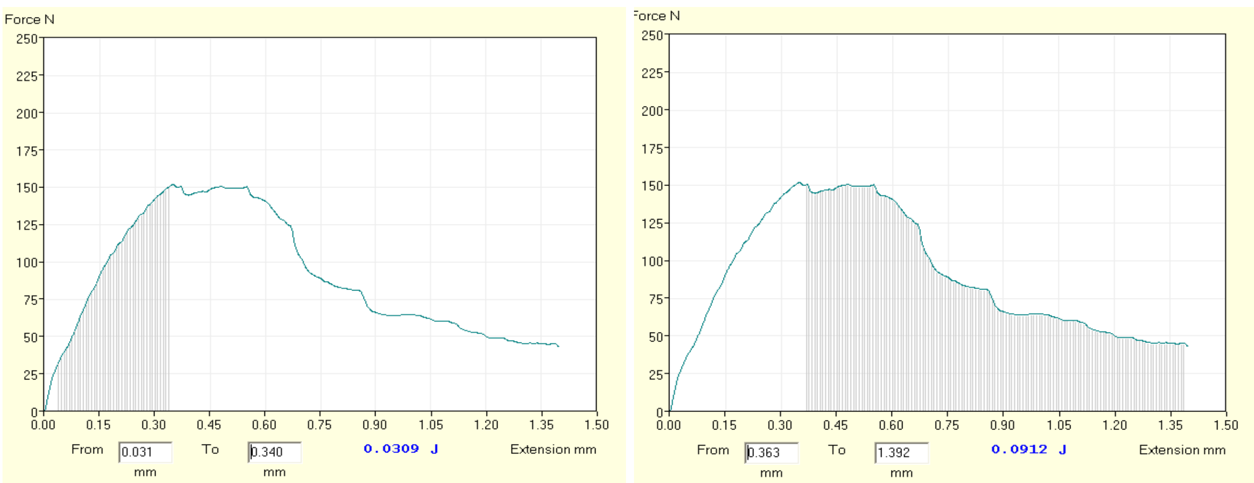
a) b) c)

Fig. 5 - Identification of the mechanical behaviour of rose hip seeds using unsupervised machine learning techniques

(a) mean force–displacement curves of the resulting clusters; (b) projection of samples in the PCA space (PC1–PC2); (c) evaluation of the optimal number of clusters using the silhouette index

The distribution of samples in the PCA space confirms the separation between the two groups. Furthermore, silhouette analysis indicates that the three-cluster solution provides the best mathematical separation of the data. However, one of the clusters is represented by a very small number of observations and can therefore be interpreted as an outlier group. Consequently, from a physical and mechanical perspective, the behaviour of the seeds can be adequately described by two principal categories of compression response. In Fig. 5b, Cluster 3 consists of a single point (or only a very small number of points). This indicates that the algorithm identifies this sample as a separate group because its mechanical characteristics differ substantially from those of the remaining data. Figure 5c shows the variation of the silhouette index as a function of the number of clusters.

Figure 6 presents a representative force–displacement curve obtained during the compression of a rose hip seed belonging to Cluster 1 (mechanically rigid/high-strength seeds). An initial increase in force can be observed up to approximately 150 N, followed by a resistance plateau associated with the redistribution of internal stresses. At a displacement of approximately 0.7 mm, a sudden drop in force occurs, indicating the primary fracture of the seed structure. Following this event, the mechanical response is characterized by a gradual decrease in force, which is typical of the progressive fragmentation and compaction of the resulting material.



(a) (b)

Fig. 6 - Representative force–displacement curve of a Cluster 1 seed (mechanically rigid/high-strength seeds)

(a) energy absorbed within the viscoelastic region and up to the yield point (E = 0.0309 J);
(b) energy absorbed after exceeding the yield point and until the end of the compression process (E = 0.0912 J)

The energy value of 0.0309 J, determined between the point corresponding to the elastic limit at a displacement of 0.031 mm and the yield point at a displacement of 0.340 mm (Fig. 6a), highlights the ability of the seed to absorb mechanical energy before the onset of irreversible deformation. This value reflects the resistance of the internal structure to compression and suggests a relatively rigid mechanical behaviour, characterized by an initial stage of controlled deformation prior to the initiation of cracking or structural failure processes. Figure 6b presents the mechanical energy absorbed by the seed within the deformation range from 0.363 mm to 1.392 mm, determined by integrating the force–displacement curve. The obtained value, 0.0912 J, reflects the seed's capacity to absorb energy after reaching the yield point, including the processes of cracking, fracture, and progressive compaction of the resulting fragments. The energy absorbed during this stage is approximately three times greater than that accumulated within the viscoelastic region, highlighting a significant capacity for energy dissipation under compressive loading.

A comparative analysis of the two energy intervals shows that approximately 75% of the total absorbed energy is dissipated after the onset of irreversible deformation. This result suggests a progressive failure mechanism of the seed structure, characterized by the successive development of cracks and the gradual fragmentation of the material, rather than by a sudden and instantaneous fracture.

Figure 7 highlights the creep behaviour of rose hip seeds subjected to a constant load of 25 N for a duration of 600 s. The final creep deformation values were 0.018 mm, 0.027 mm, and 0.067 mm for the three analysed specimens, confirming the existence of significant variability in the viscoelastic response within the experimental batch. It can be observed that, although all specimens were tested under identical conditions, the deformation recorded after 600 s differed considerably, which may be attributed to structural and geometrical differences among the seeds. The observed behaviour confirms the viscoelastic nature of the biological material and its ability to develop progressive deformation under constant loading. Furthermore, the relatively low creep displacement values indicate good structural stiffness and high resistance to permanent deformation. The obtained results suggest that rose hip seeds are capable of withstanding long-term mechanical loading with limited deformation, an important aspect for handling, transportation, storage, and mechanical processing operations.

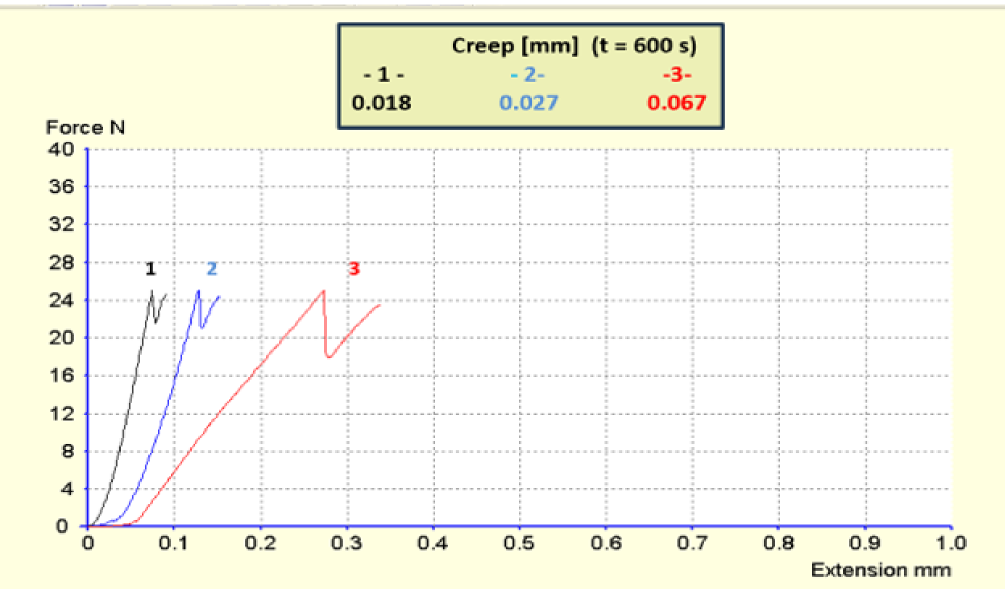


Fig. 7 – Creep behaviour of rose hip seeds under a constant load of 25 N for 600 s

Figure 8 presents the evolution of the applied force during the creep test for the three rose hip seed specimens. After reaching the maximum load of approximately 25 N, all specimens exhibited an initial decrease in the measured force, followed by a gradual increase throughout the 600 s creep period. The force increased from values ranging between 18–21.5 N to approximately 24–25 N at the end of the test. This behaviour suggests the occurrence of compaction and structural reorganization processes within the rose hip seeds, leading to a progressive increase in resistance to deformation under sustained loading. The observed response indicates that, following the initial accommodation phase, the internal structure becomes increasingly resistant to further deformation, resulting in the gradual recovery of the measured force toward the imposed load level.

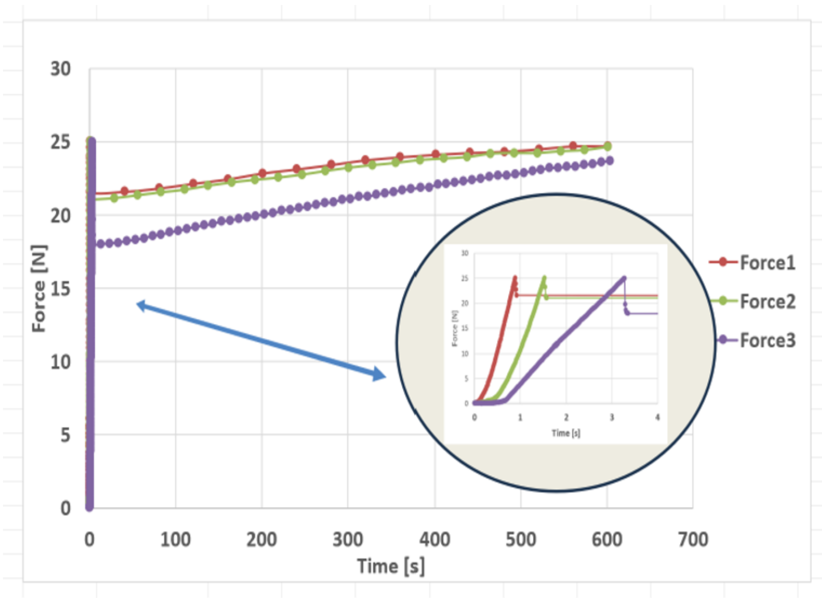


Fig. 8 – Variation of force with time during creep testing of rose hip seeds, showing the initial force decrease followed by a gradual recovery toward the imposed load of 25 N

From an experimental perspective, an interesting finding is that the force does not relax over time but instead tends to recover toward the initial value of 25 N, indicating a behaviour different from that of many conventional polymeric materials and characteristic of compact granular plant structures. After the initial compaction and local structural failure, the material does not continue to soften but rather exhibits a progressive increase in resistance to compression. This behaviour may be associated with material densification, a reduction in internal porosity, an increase in the contact surfaces between particles, and a redistribution of stresses within the seed structure. From the standpoint of granular material mechanics, the observed response resembles a strain-hardening phenomenon induced by compaction.

The force distribution over time confirms that all specimens were tested under similar loading conditions. Therefore, the differences subsequently observed in creep deformation can be attributed primarily to the specific viscoelastic properties of each seed rather than to variations in the applied load.

Figure 9 presents the variation of deformation as a function of time for the three rose hip seed specimens subjected to a constant load of 25 N for 600 s. A progressive increase in deformation can be observed for all specimens, which is characteristic of the creep behaviour of viscoelastic materials. During the initial stage of the test, an instantaneous deformation occurs, associated with the elastic component of the mechanical response, followed by a slow and continuous increase in deformation throughout the entire loading period.

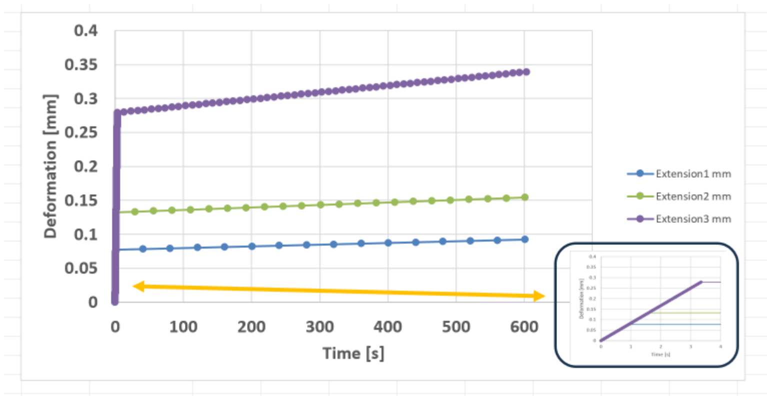


Fig. 9 - Time-dependent deformation (creep) of rose hip seeds under a constant compressive load of 25 N

Specimen 3 exhibited the highest deformation, increasing from approximately 0.28 mm to 0.34 mm after 600 s, indicating a greater susceptibility to time-dependent deformation. Specimen 2 displayed an intermediate behaviour, with deformation values ranging from approximately 0.14 mm to 0.16 mm, whereas Specimen 1 showed the lowest displacement values, approximately 0.08–0.09 mm. The differences observed among the three curves highlight the variability of the viscoelastic properties of the analysed seeds and suggest the existence of internal structural differences that influence their deformation capacity under long-term mechanical loading. Nevertheless, the relatively low slopes of the creep curves indicate good dimensional stability and high resistance to permanent deformation.

For the description of the creep behaviour of rose hip seeds, the Zener Standard Linear Solid (SLS) viscoelastic model was employed. The viscoelastic model parameters E_1, E_2, and η can be determined from the experimental creep data using the values of the initial deformation, final deformation, and deformation at an arbitrary time t. Thus, the instantaneous elastic modulus E_1 can be determined using the following relationship:

$$E_1 = \frac{3P0}{8R} \cdot \frac{1}{\delta(0)} \tag{3}$$

where $\delta(0)$ represents the initial penetration depth, or the instantaneous deformation, occurring immediately after the application of the constant load P_0.

The modulus E_2, associated with the delayed elastic component, can be determined using the following relationship:

$$E_2 = \frac{3P0}{8R} \cdot \frac{1}{\delta(\infty) - \delta(0)} \tag{4}$$

where $\delta(\infty)$ represents the asymptotic deformation reached at a very long time, corresponding to the equilibrium state of the creep process under the applied constant load.

The dynamic viscosity coefficient η can be calculated using the following relationship:

$$\eta = \frac{P0 \cdot t}{8R} \cdot \frac{1}{[\delta(\infty) - \delta(0)] \cdot \ln[\frac{\delta(\infty) - \delta(0)}{\delta(\infty) - \delta(t)}]} \tag{5}$$

Considering the applied load P_0 and the indenter radius R = 1.4 mm, the instantaneous elastic modulus E_1 and the delayed elastic modulus E_2 were determined using Eqs. (3) and (4). The viscosity coefficient η was calculated using Eq. (5) for a creep time of t = 300 s. The obtained values are summarized in Table 1.

Table 1

Experimental creep parameters and viscoelastic parameters determined using the Zener model for rose hip seeds

Sample	$P0$ [N]	$\delta(0)$ [mm]	$\delta(600)$ [mm]	E_1 [GPa]	E_2 [GPa]	η [GPa·s]
1	21.57	0.074	0.092	0.078	0.321	46.308
2	21.05	0.128	0.155	0.044	0.209	30.128
3	18.03	0.281	0.34	0.018	0.072	10.399

The results reveal a progressive decrease in the elastic moduli E_1 and E_2 from Specimen 1 to Specimen 3, indicating a reduction in structural stiffness and an increase in material deformability. Similarly, the viscosity coefficient η exhibits decreasing values, suggesting a lower resistance to time-dependent deformation. Specimen 1 displays the most rigid viscoelastic behaviour, whereas Specimen 3 is characterized by the greatest susceptibility to creep and progressive deformation under constant loading.

The literature indicates that cereal grains exhibit time-dependent and viscoelastic mechanical behaviour, although at low loads and short loading times the elastic response may become predominant and the load–deformation relationship remains approximately linear (*Mohsenin, 1966; Shelef and Mohsenin, 1967*). Similarly, the rose hip seeds investigated in the present study exhibited a time-dependent response under constant loading; however, the 600 s creep tests enabled the progressive deformation and associated viscoelastic behaviour to be clearly identified.

For biological materials considered nearly incompressible, the evolution of the penetration depth (deformation) over time can be expressed by the following relationship (*Cheng et al., 2000*):

$$\delta(t) = \frac{3P0}{8RE1}[-(\frac{E1}{E2})\, e^{-(\frac{E2}{3\eta})t} + (1 + \frac{E1}{E2})] \tag{6}$$

Following the approach used by *Shelef and Mohsenin (1967)* for cereal grains, the influence of Poisson's ratio may be expressed through the correction factor $k = 1 / (1 - \nu^2)$, with $1 < k < 1.33$.

This range corresponds mathematically to $0 < \nu < 0.49$. Since Poisson's ratio was not independently determined for the rose hip seeds investigated in the present study, the calculated elastic parameters should be regarded as apparent, model-dependent values rather than intrinsic material constants.

The relatively limited number of compression specimens (n = 25) should be considered when interpreting the PCA/K-means results, which are therefore regarded as exploratory evidence of natural patterns within the investigated batch rather than as a definitive population-level classification. Regarding the creep experiments (n = 3), despite the limited number of specimens, a relatively consistent time-dependent response was observed under identical loading conditions, with the differences being mainly associated with seed dimensions. Considering this consistency and the relatively long duration of each individual test (600 s), the three experiments were considered adequate for a descriptive assessment of the creep phenomenon within the scope of the present study, without claiming statistical representativeness for the entire rose hip seed population.

A limitation of the present study is the crosshead speed of 15 mm/min used during compression testing, which is higher than the loading rates commonly employed for strictly quasi-static testing of agricultural biological materials. Therefore, a possible influence of the loading rate on the measured force–deformation response cannot be excluded. Future studies should investigate lower loading rates and systematically evaluate their effects on maximum compression force, stiffness, deformation energy, and fracture behaviour.

CONCLUSIONS

The exploratory application of unsupervised machine learning techniques (PCA and K-means) to the mechanical features extracted from the compression tests enabled the identification of natural groups of mechanical behaviour. The results revealed two main categories within the investigated seed batch: one group characterized by high mechanical strength and stiffness, and a second group exhibiting greater deformability and lower resistance to compression.

The Zener (SLS) viscoelastic model made it possible to determine the parameters E_1, E_2, and η, revealing differences in the time-dependent mechanical response of the tested specimens. The progressive decrease in the elastic moduli and viscosity coefficient was associated with increased deformability and reduced resistance to creep.

The proposed methodology, combining conventional mechanical testing with modern data analysis and unsupervised machine learning techniques, provides a useful approach for investigating the mechanical behaviour of rose hip seeds and may be extended to other biological materials used in the food and pharmaceutical industries.

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