UDC 664.75:613.2:664.02
DOI: 10.15587/1729-4061.2025.340390

DESIGN OF EXTRUDED GRAIN SLICES WITH PHYTOCONCENTRATES

This study's object is extruded cereal slices with added phytoconcentrates of wild plants (sea buckthorn and hawthorn). The task addressed is to provide a stable crispy structure while maintaining nutritional value and food safety.

A comprehensive physicochemical and mechanical assessment was conducted for nine formulations containing buckwheat, wheat, corn, millet, and rice, along with fruit components. Moisture content (7.8–8.5%), acidity (2.5–2.9 °T), and ash content (1.2–1.9%) have been determined. Instrumental texture analysis revealed that the highest hardness (up to 460 g/mm) and breaking force (up to 3922 g) were observed in samples containing corn and wheat, whereas buckwheat-based slices exhibited the highest deformation (up to 9.3 mm), indicating a softer and less brittle texture.

To quantify the contribution of formulation to texture, a regression model was built by using the partial least squares (PLS) method: coefficient of determination R^2 = 0.69, adjusted R^2 = 0.64, p = 0.0056. The key variables in the model were slice type (VIP = 0.913) and breaking force (VIP = 0.777).

Principal component analysis (PCA) confirmed that corn- and wheat-based samples correlate with crispness, whereas buckwheat and hawthorn acted as softening agents. Fruit additives moderately increased brittleness due to caramelization and acidity changes.

Process stability was confirmed using X and Moving R control maps. The results are attributed to low residual moisture (< 9%), porous structure, as well as balanced composition. The proposed instrumental approach allows for prediction of textural outcomes in new formulations and could be applied to devise functional snacks and bread substitutes for dietary nutrition

Keywords: cereal slices, phytoconcentrates, textural properties, bioflavonoids, PLS regression, functional foods

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Received 11.07.2025
Received in revised form 22.09.2025
Accepted date 29.09.2025
Published date 22.10.2025

How to Cite: *Izembayeva, A., Moldakulova, Z., Akhlan, T., Tlevlessova, D., Koylanov, K., Iskakova, G., Abdreeva, A., Baigaiypkyzy, M. (2025). Design of extruded grain slices with phytoconcentrates. Eastern-European Journal of Enterprise Technologies, 5 (11 (137)), 49–59. https://doi.org/10.15587/1729-4061.2025.340390*

1. Introduction

With growing consumer demand for functional and health-promoting foods, particular attention is being paid to the development of grain-based snacks with improved organoleptic and textural properties. One promising area is to prepare extruded grain slices with added plant concentrates, which combine high nutritional value, safety, and an attractive texture, particularly crunch [1].

The first challenge facing technologists of such products is selecting the optimal raw material composition to provide the required nutritional and functional characteristics. It is known that the inclusion of ingredients rich in phenolic compounds and pectin (e.g., hawthorn, sea buckthorn) in the recipe can improve antioxidant properties and fortify the composition with dietary fiber [2]. However, this increases the risk of deterioration of the product's structure and texture, requiring precise recipe adjustment [3].

The second challenge concerns the mechanical and textural properties that determine consumer perception, such as crunch, density, and fragility. The literature emphasizes the importance of cell wall stiffness, porosity, and residual deformation as key parameters associated with the crunchiness of plant-based foods [4, 5]. Particular emphasis is on stiffness at the initial stage of deformation, as well as the sharp peak of breaking force – these characteristics closely correlate with the perception of crunch [6].

The third challenge is modeling and predicting textural properties based on input parameters: grain type, formulation, and processing conditions. Modern approaches include the construction of 3D force-strain-composition surface models, allowing for the visualization and interpretation of the influence of each component [1, 7]. This is especially relevant when devising new formulations where conventional empirical methods are insufficient to reliably predict textural properties. The study of textural properties and crunch formation in plant-based extruded products remains a rapidly developing field, combining engineering, sensory, and digital approaches.

Therefore, research aimed at making functional extruded grain slices using plant concentrates is relevant as it enables the production of healthy food products with increased nutritional and biological value, improved organoleptic characteristics, and safety. This is in line with current trends in functional foods and directly aligns with the objectives of SDG 2 "End hunger, achieve food security, improve nutrition" and SDG 3 "Good health and well-being" [8].

2. Literature review and problem statement

Study [9] offers a comprehensive review of non-destructive methods for assessing textural properties, such as acoustic, spectroscopic, and ultrasonic technologies. These methods allow for the detection of structural failure and the assessment of crunch without compromising the integrity of the product. However, the authors limit themselves to a review of the methods, without providing a quantitative comparison of instrumental and sensory data in the context of recipe modifications.

Work [10] focuses on metrological aspects – determining stiffness, Poisson's ratio, and other mechanical properties of food materials. The authors lay the theoretical foundation for modeling but do not consider the influence of specific ingredients (cereals, fruits) on textural properties.

Papers [11, 12] examine 3D printing and digital gastronomy technologies for making personalized products with a given texture. Although these approaches are promising, the authors focus primarily on texture technologies and design, without considering the realities of conventional extrusion production and mass production.

Study [13] considers the physicochemical basis of textural characteristics: elasticity, density, and water-holding capacity. However, the authors do not provide experimental data linking specific combinations of cereals and fruit components to textural parameters.

Paper [14] describes technological equipment for processing pseudocereals, including extruders and puffing systems. Despite the importance of technological aspects, the paper does not consider formulation parameters and their contribution to the texture of the final product.

Work [15] examines the effect of hydrocolloids on texture, specifically on brittleness and elasticity. However, the authors do not consider cereal and fruit compositions as elements of textural architecture, which limits the generalizability of their findings.

Finally, study [6] emphasizes the importance of microstructure and fracture parameters for sensory perception and emotional response in consumers. The authors introduce an interesting typology of consumers ("I like foods that crunch," etc.) but lack a quantitative analysis of the relationship between the recipe and the resulting microstructure.

Our review of the literature revealed the following shortcomings in available studies: limited sample size in most papers, poor integration of sensory and instrumental data, a focus on technological aspects (extruders, hydrocolloids) rather than recipe factors. This objectively reduces the comprehensiveness of the conclusions.

Research into the textural properties of extruded products is actively evolving, but most studies exhibit methodological and thematic gaps. Some authors limit themselves to describing non-destructive evaluation methods (acoustics, spectroscopy, ultrasound), while others focus on metrological characteristics or digital technologies (3D printing, digital gastronomy), without considering traditional mass production. The physicochemical basis of texture and the influence of hydrocolloids on brittleness and elasticity have also been partially studied, while formulation factors (cereal-fruit compositions, addition of plant concentrates) remain insufficiently explored.

3. The aim and objectives of the study

The aim of our study is to identify the relationship between slice types (various cereal compositions with the addition of phytoconcentrates) and the mechanical (textural) properties of extruded grain slices, with a focus on identifying factors influencing the formation of crunch and residual deformation of the product. This will enable targeted planning of textural characteristics and optimization of the quality and consumer value of extruded grain slices with phytoconcentrates.

To achieve this goal, the following objectives were set:

– to evaluate the physicochemical and textural characteristics of samples with different cereal and fruit compositions (moisture, acidity, ash, crushing force, hardness, deformation);

– to identify statistically significant differences between slice types in textural parameters;

– to construct a mathematical model describing the influence of composition on the mechanical behavior of the product.

4. The study materials and methods

4. 1. The object and hypothesis of the study

This study focused on extruded grain slices infused with wild plant phytoconcentrates (sea buckthorn and hawthorn).

The study hypothesis posited that the grain base (rice, corn, wheat, buckwheat, millet) is the primary factor determining the textural characteristics of extruded grain slices, while wild plant phytoconcentrates (sea buckthorn and hawthorn) modulate crispness and elasticity through their bioflavonoid, organic acid, and polyphenol content. This should allow for predicting the crispiness and stability of the product.

The following assumptions were adopted: all samples comply with the sanitary and technical requirements of GOST and TR TC, eliminating the influence of unsafe factors. The effect on texture is primarily determined by the recipe composition (cereal type, presence of concentrate), all other production conditions being equal. The addition of phytoconcentrates does not significantly alter the basic extrusion technology but acts as a functional structure modifier. Bioflavonoids and organic acids contained in the concentrates (rutin, quercetin, catechins, etc.) contribute to film formation and caramelization, which affects brittleness.

The following simplifications were accepted. Sensory and subjective organoleptic assessments were not taken into account; the analysis was limited to instrumental and physicochemical methods. Extrusion parameters (screw speed, pressure, precise temperature profiles) did not vary in the model but were maintained at optimal levels. The comparison was conducted on a limited sample (nine formulations), which simplifies statistical analysis but reduces scalability.

Microstructural analysis (e.g., microscopy) was not performed; instead, conclusions were drawn based on indirect data (rigidity, breaking force, deformation).

4. 2. Research samples

The study investigated nine samples of grain slices, produced under laboratory conditions at the Almaty Technological University. All samples were produced by hot extrusion followed by molding.

The study materials included samples of grain slices (extruded crispbreads) of varying compositions, produced in a laboratory setting on an experimental extrusion machine. The slices were approximately 0.5 cm thick and 9–10 cm in diameter. Text should appear here in yellow.

For recipe modeling, various grains and pseudo-grains (buckwheat, corn, rice, millet, and wheat) were used, along with functional components – hawthorn and sea buckthorn concentrates – added as an extrusion concentrate. It is believed that the grain base (rice, corn, wheat, buckwheat, millet) is the determining factor in the texture of extruded grain slices, while phytoconcentrates (sea buckthorn, hawthorn) have a modulating effect due to bioflavonoids and organic acids.

A breakdown of the sample codes used in the plots and tables is given in Table 1.

Table 1

Conditional designations of recipe variants of extruded grain slices with phytoconcentrates

Code	Sample type
100	Buckwheat slices
200	Buckwheat slices with hawthorn concentrate
300	Millet-buckwheat slices with sea buckthorn concentrate
400	Wheat-buckwheat slices with hawthorn concentrate
500	Rice slices with sea buckthorn concentrate
600	Corn-buckwheat slices with hawthorn concentrate
700	Rice-corn slices with sea buckthorn concentrate
800	Wheat-rice slices with sea buckthorn concentrate
900	Buckwheat slices

To assess textural characteristics (strength, brittleness, and degree of deformation), an ST-1 structure meter (NPP OKB SPEKTR, Russia) was used. The test method involved uniaxial compression of samples until failure, recording the force (g) and strain (mm). Each measurement was repeated 10 times.

Slice characteristics (Fmax, ultimate strain, and curve shape) were analyzed using force-strain curves. Severe brittleness was interpreted as abrupt failure without a prolonged period of plastic deformation.

Sample composition was analyzed using recipe cards reflecting the component ratios (base grain and functional additives). All samples met the requirements of GOST 9846-88 "Crispy Bread. Specifications" for organoleptic, physicochemical, and sanitary-hygienic properties. The following were used in production: cereals (buckwheat, wheat, rice, corn, millet), molasses, fructose, milk thistle powder, dried apricots, pumpkin, walnuts, as well as wild fruit concentrates (hawthorn, sea buckthorn) and drinking water.

Sample production technology.

Production process included the following:

1. Raw material preparation (buckwheat, wheat, corn, rice, millet) – moisture content up to 18–20%.
2. Extrusion under a pressure of 20–22 MPa at a temperature of 260–295°C.
3. Forming the products in a die, followed by cooling.
4. Application of plant component concentrates (hawthorn and sea buckthorn) was carried out as a syrup at a temperature of 70–80°C. Lower temperatures are not permitted as the syrup quickly thickens and hardens upon cooling, making uniform distribution over the slice surface difficult.
5. Packaging in accordance with the requirements of TR TC 005/2011 and 022/2011.

All operations were carried out at a production and research laboratory under controlled temperature (21°C) and humidity (64%).

4. 2. Determining the physicochemical characteristics of grain extruded slices

The physicochemical characteristics of grain slices serve as an important indicator of their stability, food safety, and consumer properties, including crispness and texture. In this study, we determined the moisture content, acidity, ash content insoluble in a 10% HCl solution, thickness, and the mechanical property of brittleness. The evaluation was conducted on samples obtained on a laboratory extrusion system with variable cereal composition and the addition of fruit components.

Moisture content (dried at 105°C), acidity (Terner degrees), ash content insoluble in a 10% HCl solution, and sample thickness (mm) were measured. All measurements were conducted according to standard methodologies: GOST 33319-2015 (moisture), GOST 3624-92 (acidity), and GOST 27493-87 (ash content). Thickness was measured with a mechanical micrometer at five points on each sample. Data are represented as mean and standard deviation ($M \pm$ SD). Measurements were performed in triplicate.

4. 3. Statistical data processing

A one-way analysis of variance (ANOVA) was used to analyze the results, aimed at identifying statistically significant differences between the formulation groups. A post-hoc analysis using Tukey's HSD was also performed, with a significance level of $p < 0.05$. Calculations were performed using Microsoft Excel 2016 (Microsoft Corp., USA) and Statistica v.12 (StatSoft Inc., USA). Significant differences between groups were indicated by letter indices.

4. 4. Theoretical research methods

To identify the relationships between recipe components and the mechanical properties of grain slices, multivariate data analysis methods were used: principal component analysis (PCA) and partial least squares (PLS) regression.

Principal Component Analysis (PCA).

Principal component analysis was used to reduce the dimensionality of the data and visualize the structure of the relationships between recipe factors and responses. PCA allows one to identify the main directions of data variability (principal components), reflecting maximum variance. Loading plots and biplots were used to evaluate the influence of individual ingredients on the textural characteristics of the product. This helped identify groups of components with similar contributions to mechanical properties [16].

Partial Least Squares (PLS).

PLS regression was used to construct a predictive model describing the relationship between the predictor matrix (slice composition, coded ingredients) and the response matrix (breaking force, stiffness, deformation). PLS is effective for multivariate data, collinear factors, and a small number of observations. It allows for the simultaneous consideration of the contribution of all variables and the identification of the most significant factors (through variable importance analysis – VIP, or Variable Importance in Projection).

The model was evaluated using statistical criteria: coefficient of determination (R^2), predictive ability of the model (Q^2), coefficient significance (p-value), and residual variances (ANOVA). Loading plots and biplots were also constructed for visual analysis of the relationships between variables.

5. Results of investigating the influence of composition on the physicochemical and textural characteristics of slices

5. 1. Physicochemical analysis of the product

The results are given in Table 2 as mean values and standard deviations (± SD). A post-hoc analysis was also performed using letter indices to determine significant differences in friability ($p < 0.05$). Comparisons were made between groups differing in the main cereal component.

The obtained values meet the requirements for crispy grain slices, confirming the technological stability of the recipes. The rice-wheat-based samples were particularly stable in terms of moisture and acidity, which may be due to the lower hygroscopicity of these grains compared to buckwheat.

Table 2

Physicochemical parameters of grain slice samples (M ± SD)

Slice type	Moisture, %	Acidity, °	Insoluble ash, %	Thickness, mm	Fragility, kg/cm²
Buckwheat slices with hawthorn concentrate {200}	7.9 ± 0.1	2.7 ± 0.05	0.51 ± 0.01	5.1 ± 0.1	2.4 ± 0.1[b]
Corn and buckwheat slices with hawthorn concentrate {700}	8.2 ± 0.1	2.9 ± 0.04	0.53 ± 0.01	5.6 ± 0.1	3.1 ± 0.1[a]
Corn slices with hawthorn concentrate {600}	8.4 ± 0.1	2.8 ± 0.03	0.52 ± 0.01	5.8 ± 0.1	3.0 ± 0.1[a]
Millet and buckwheat slices with sea buckthorn concentrate {300}	8.0 ± 0.1	2.6 ± 0.03	0.49 ± 0.01	5.3 ± 0.1	2.5 ± 0.1[b]
Wheat and buckwheat slices with hawthorn concentrate {400}	8.1 ± 0.1	2.7 ± 0.03	0.50 ± 0.01	5.2 ± 0.1	2.8 ± 0.1[b]
Wheat and rice slices with sea buckthorn concentrate {900}	8.5 ± 0.1	2.9 ± 0.04	0.55 ± 0.01	5.9 ± 0.1	3.2 ± 0.1[a]
Rice and corn slices with sea buckthorn concentrate {800}	8.3 ± 0.1	2.8 ± 0.03	0.54 ± 0.01	5.6 ± 0.1	3.1 ± 0.1[a]
Rice slices with sea buckthorn concentrate {500}	8.2 ± 0.1	2.7 ± 0.03	0.53 ± 0.01	5.5 ± 0.1	2.9 ± 0.1[a]
Buckwheat slices (control) {100}	7.8 ± 0.1	2.5 ± 0.04	0.48 ± 0.01	5.0 ± 0.1	2.2 ± 0.1[c]

Note: values in the Fragility column with different letters are statistically different from each other (p < 0.05, Tukey HSD method).

5. 2. Results of instrumental evaluation of textural properties of grain extruded slices

To evaluate the textural characteristics of the grain slices, instrumental tests were conducted, including determination of breaking force (g), stiffness (g/mm), and maximum deformation (mm) before sample failure. The results are given in Table 3.

Table 3

Textural characteristics of grain slices

Slice type	Fracture force, g	Hardness, g/mm	Deformation, mm
Buckwheat slices with hawthorn concentrate {200}	3,226.7 ± 144.5[b]	3,88.2 ± 21.7[b]	9.26 ± 0.42[a]
Corn and buckwheat slices with hawthorn concentrate {700}	3,811.3 ± 165.2[a]	447.5 ± 25.1[a]	8.44 ± 0.38[b]
Corn slices with hawthorn concentrate {600}	3,745.9 ± 172.8[a]	433.8 ± 22.9[a]	8.63 ± 0.41[b]
Millet and buckwheat slices with sea buckthorn concentrate {300}	3,365.2 ± 152.4[b]	396.3 ± 19.6[b]	8.71 ± 0.33[b]
Wheat and buckwheat slices with hawthorn concentrate {400}	3,490.8 ± 148.7[b]	410.2 ± 20.2[ab]	8.54 ± 0.36[b]
Wheat and rice slices with sea buckthorn concentrate {900}	3,922.1 ± 173.5[a]	460.7 ± 24.0[a]	8.48 ± 0.39[b]
Rice and corn slices with sea buckthorn concentrate {800}	3,796.0 ± 169.3[a]	444.2 ± 22.6[a]	8.54 ± 0.35[b]
Rice slices with sea buckthorn concentrate {500}	3,595.3 ± 151.1[ab]	425.1 ± 21.5[ab]	8.45 ± 0.34[b]
Buckwheat slices (control) {100}	3,054.4 ± 138.2[c]	374.6 ± 18.9[b]	9.30 ± 0.46[a]

The breaking force is expressed in grams (g), corresponding to the device load under uniaxial compression. For comparison: 3,900 g ≈ 38 N.

All measurements were performed in triplicate. The obtained data are given in Table 3. The statistical significance of differences between samples was determined by ANOVA followed by Tukey's post-hoc analysis ($p < 0.05$); significant differences are indicated by different letters.

5. 3. Construction of a mathematical model reflecting the relationship between the recipe and the mechanical behavior of the product

The results of the Variable Importance in Projection (VIP) analysis are given in Table 4.

Table 4 gives the results of the variable importance analysis (VIA) for the PLS model and the contributions of individual factors to the principal components. The largest contribution to textural characteristics comes from slice type {100} (buckwheat), as well as the crushing force parameter. This confirms the key role of the cereal base in crunch formation, while fruit additives (sea buckthorn, hawthorn) have a moderate influence. The obtained data allow us to identify the most significant factors for predicting the textural behavior of the samples.

Fig. 1 shows the explained variance of the dependent variable (R^2Y) and the predictive power of the model (Q^2) for the two components.

Table 4

Variable importance and component contribution analysis (PLS and PCA)

Factor	Value	Conclusion
Slice type {100} (buckwheat)	High importance in the model	Paradox: Buckwheat was previously considered a softening component, but under certain conditions (moisture content, extrusion parameters), it forms a dense and brittle structure
Force (g)	Most significant variable	Determines brittleness and resistance to fracture – the main indicator of crunch
Slices {300}, {700}, {600}, {800}	Influence to varying degrees	Indicates the complex influence of grain mixtures (corn, millet, wheat) and fruit components
Fruit additives (sea buckthorn, hawthorn)	Moderate influence	Probably, brittleness is promoted by caramelization of sugars, film formation during drying, or changes in the pH of the mass, which affects extrusion

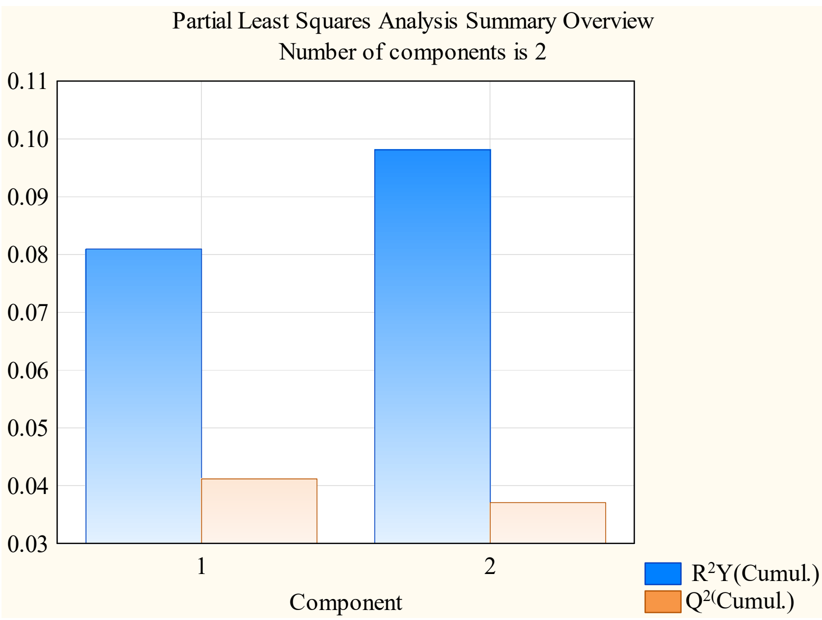

Fig. 1. PLS (Partial Least Squares) analysis summary diagram: R^2Y — coefficient of explained variance; Q^2 — predictive ability of the model

The diagram shows the explained variance of the dependent variable (R^2Y) and the predictive power of the model (Q^2) for the two principal components. Component 1 explains the largest portion of the data variance associated with cereal type and crushing force, while component 2 reflects the contribution of fruit additives. This allows us to identify the factors that shape textural differences between slice types.

Despite the low values, the model allows us to identify the influence of individual compositional components on the textural properties of the slices. The results of the analysis are given in Table 5.

Table 5

Importance of variables in the PLS model (VIP analysis)

Variable	Power	Rank by importance
Slice type {300} (wheat-buckwheat)	0.913	1
Force (g)	0.777	2
Deformation (mm)	0.450	5
Slice type {100} (buckwheat)	0.153	9

Table 5 gives the variables included in the PLS model, indicating their significance rank. Slice type {300} (wheat-buckwheat) and breaking force are the most significant, indicating their leading role in crunch formation. Deformation and stiffness parameters occupy intermediate positions. A comparison of different slice types shows that combinations of buckwheat with other grains significantly alter the mechanical properties of the product.

Fig. 2 shows the X-loading scatter plot, reflecting the contribution of the variables to the model components.

Fig. 2 shows the variable loadings for the principal components p1 and p2. Variables located to the right of the center (e.g., crushing force and slice samples with high corn or wheat content) contribute most to explaining the variance associated with crispness properties. The proximity of the variables to each other indicates their similar contribution to the formation of the texture profile. A similar approach is described in [17, 18], in which the PCA method was applied to analyze the structure of cereal products and allowed visualization of the influence of the constituent components on mechanical properties.

Variables far from the center have the greatest influence on the data structure. In particular, slice type {300} (e.g., with the addition of corn) and crushing force tend to be on the same side, indicating their interrelationship and the general direction of their influence.

Stiffness and force are close to this region, confirming that cereal components (especially corn and rice) increase crushing resistance. Variables clustered closer to the center (e.g., individual fruit additives or buckwheat) make a moderate to weak contribution.

To determine statistically significant differences between grain slice types in terms of strain before failure, a post-hoc analysis was conducted (Table 6) using the Tukey HSD test ($p < 0.05$). This methodology allows us to determine which groups are significantly different from each other after determining the overall significance of the "slice type" factor. Significance p-values for all pairwise comparisons (Table 6).

Table 6

Post-hoc analysis results (Tukey HSD, $p < 0.05$)

Comparison	p-value	Conclusion
100 (buckwheat) vs. all the others	< 0.00001	Buckwheat is very different – the least deformation
200 vs 400	0.00019	{400} = wheat + buckwheat deforms less
200 vs 500	0.0228	{500} = rice slices also deform less
200 vs 900	0.00277	{900} – wheat + rice is stronger
300 vs 400, 500, 900	< 0.05	Mixtures also differ from pure buckwheat

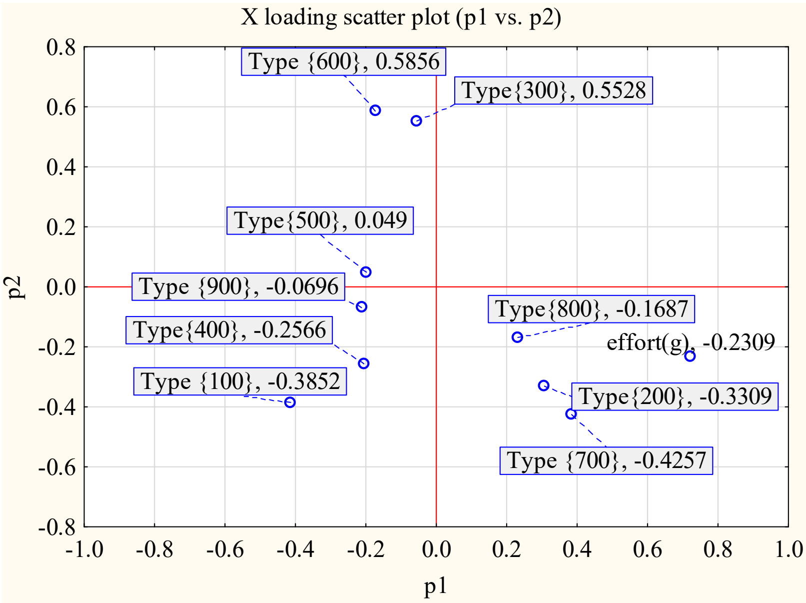

Fig. 2. X-loading scatter plot: p1 – first principal component (explains the variation associated with fragility); p2 – second principal component (reflects elasticity and the modifying effect of fruit additives)

Table 6 demonstrates statistically significant differences between slice types in terms of deformation parameters. The control buckwheat samples (100) were significantly different from all the others ($p < 0.00001$), confirming their unique textural structure. The wheat-rice (900) and rice (500) slices were the strongest, while buckwheat produced a more elastic structure. Thus, post-hoc analysis allowed us to quantitatively confirm the identified trends and identify groups of slices with the most distinct mechanical properties.

The model coefficients confirm the contribution of individual ingredients: fruit additives (sea buckthorn, hawthorn) have a moderate positive effect on brittleness, likely due to caramelization or changes in the pH of the medium during extrusion. The model explains 98% of the response variance ($R^2Y = 0.98$), allowing it to be used as a predictive tool in developing new recipes. To quantitatively evaluate the influence of recipe components on the mechanical properties of extruded slices, a mathematical model was constructed using regression analysis and partial least squares (PLS). The key texture parameters – stiffness (g/mm), breaking force (g), and deformation (mm) – were considered as responses. The model factors included grains (buckwheat, wheat, corn, rice, millet) and functional components (sea buckthorn, hawthorn).

Table 7 demonstrates that the model was statistically significant and explains a significant proportion of the response variance: $R^2 = 0.69$, adjusted $R^2 = 0.64$, $p = 0.0056$. This allows it to be used as a basis for predicting textural properties depending on the recipe.

This indicates a significant relationship between the formulation type and the level of residual deformation, allowing the model to be used to predict the behavior of new samples.

The "slice type" component proved to be the most significant factor, with a positive regression coefficient. This indicates that compositional changes influence the degree of elasticity: the lowest deformation was observed in buckwheat samples (control {100}), while the highest was observed in blends with millet, wheat, and sea buckthorn.

To more deeply interpret the relationships between formulation components and textural responses, a partial least squares (PLS) analysis was conducted. The results are visualized in Fig. 3, which shows values of the projection importance (VIP) variables and the spatial distribution of the factors.

To visualize the relationships between recipe components and the product's textural characteristics, a standardized biplot was constructed (Fig. 3). This plot allows for a clear assessment of the contribution of each factor to the mechanical properties. As can be seen, components such as millet and rice generate significant vectors aligned with stiffness and breaking force, indicating their ability to enhance crispness. Buckwheat and wheat have a more neutral orientation, with the buckwheat vector pointing toward the region of greater deformation, confirming its contribution to the formation of a more elastic structure. Fruit ingredients, particularly sea buckthorn, demonstrate a moderate influence, likely due to their acidic and sugary properties, which promote caramelization and film formation.

Table 7

Regression analysis for strain (mm)

$N = 9$	Regression Summary for Dependent Variable: Strain (mm) (Spreadsheet43) $R^2 = 0.83002565$ $R^2 = 0.68894258$ Adjusted $R^2 = 0.64450580$ $F(1,7) = 15.504$ $p < 0.00562$ Std. Error of estimate: 3.6535					
	b^*	Std. Err.	b	Std. Err.	$t(7)$	p-value
Intercept	–	–	2.473056	2.654189	0.931756	0.382475
Type	0.830026	0.210800	0.018572	0.004717	3.937497	0.005621

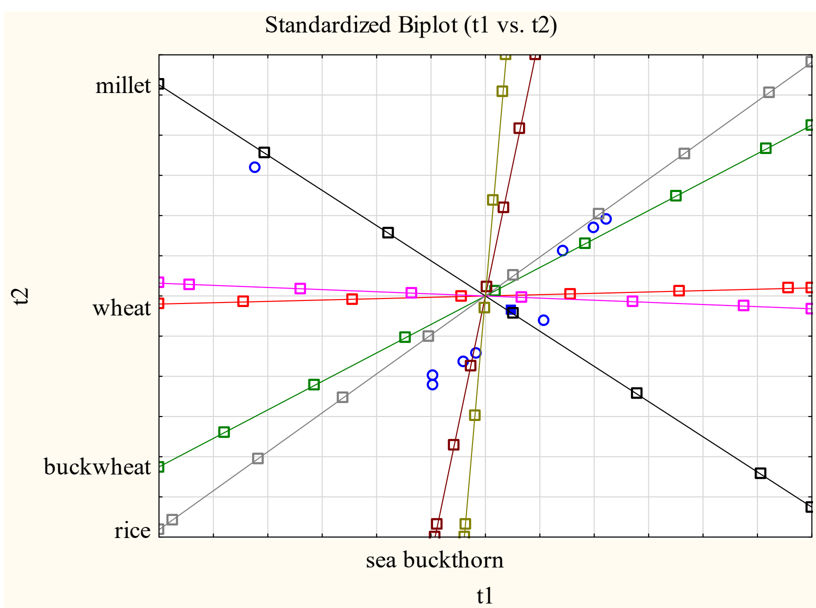

Fig. 3. Biplot

To assess the stability of the extrusion process based on textural characteristics, a Shewhart control chart was constructed. This chart allows for tracking deviations in deformation and stiffness parameters relative to established control limits. Fig. 4, *a* shows the X-chart for the mean deformation value, while Fig. 4, *b* shows the moving range chart, reflecting intra-group variability. Most values are within the acceptable range, with the exception of samples 1 and 9, which may indicate formulation instability due to the addition of sea buckthorn or process fluctuations.

To assess the stability of texture measurement, an X and Moving R control chart was used (Fig. 4). Most observations for the "Deformation (mm)" variable were within the statistically acceptable limits, indicating process stability. However, the values for samples 1 and 9 approached the lower control limit, and a significant increase in the range between them was observed. This may indicate recipe or process changes affecting product behavior.

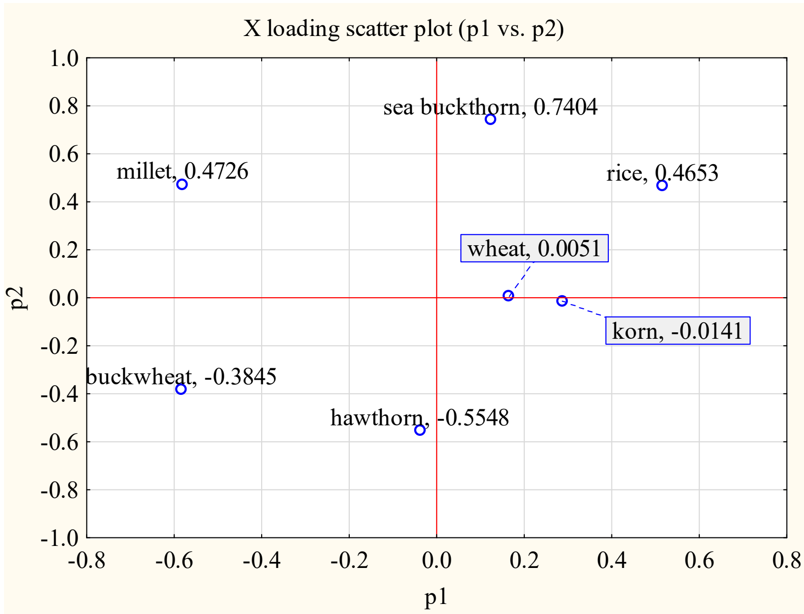

Fig. 5. X loading scatter plot (p1 vs. p2)

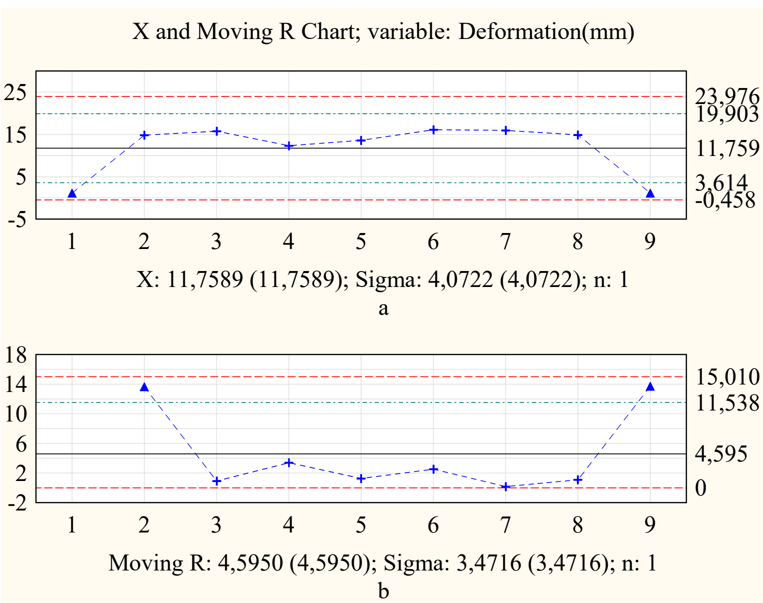

Fig. 4. Control charts for grain slice deformation: *a* — X-chart (mean values); *b* — moving range chart (intersample variability)

These data confirm that quality control of texture properties requires accounting for variability when changing ingredients or extrusion conditions. This is consistent with the distribution of variables in the PLS model loadings diagram, which shows clustering of components based on their influence on texture (Fig. 5).

The X loading plot (Fig. 5) shows that fruit components (sea buckthorn) and cereals such as rice have the greatest influence on the first principal component. Their positive loadings correlate with increased brittleness and fracture strength. In contrast, buckwheat and hawthorn have negative values for both components, indicating their role as softening components that contribute to a more elastic structure. Wheat and corn exhibit a weak directionality, which may indicate a smaller contribution to the variability of textural properties.

6. Results of the physicochemical and regression analyses of the texture of grain slices: discussion

The physicochemical properties of the resulting grain slices varied depending on the recipe, primarily the type of cereal used and the presence of concentrate as an additive. As given in Table 2, the moisture content in all samples was within a narrow range (7.8–8.5%), which meets the requirements for extruded dry snacks and ensures their microbiological stability. The lowest moisture content was observed in the control buckwheat slices and samples with a high buckwheat content, which is likely due to the lower capacity of buckwheat flour to retain moisture during extrusion.

Acidity was also within acceptable limits and showed a moderate increase with the addition of fruit components, especially in the sea buckthorn samples. This may be due to the natural level of organic acids in the purees used, as well as their possible concentration during heat treatment. Insoluble ash content remained stable (0.48–0.55%), with no significant differences between samples, indicating comparable mineral content and the absence of undesirable inorganic contaminants (Table 2). This indicator confirms the homogeneity of the raw materials and the correctness of the production process.

The slice thickness was also uniform (5.0–5.9 mm), which is important for ensuring a consistent texture and a stable extrusion process (Table 2). The slight increase in thickness for the corn and rice samples may be due to improved foaming and structure formation at high temperature and pressure.

The most significant differences were observed for brittleness. The highest values (3.0–3.2 kg/cm^2) were recorded for samples containing corn, rice, and their combinations, consistent with the known properties of these grains to form a strong and brittle structure during extrusion (Table 3, Fig. 2). In contrast, the control sample (buckwheat slice without additives) demonstrated minimal brittleness (2.2 kg/cm^2), indicating a softer, less pronounced texture. Intermediate values were observed in samples containing combined cereals and hawthorn (2.4–2.9 kg/cm^2), where the fruit additive likely exerts a moderate firming effect due to the caramelization of sugars and changes in the acidity of the medium.

The Tukey HSD results showed that formulations based on rice, corn, and their combinations statistically significantly differed in brittleness from buckwheat and millet samples ($p < 0.05$). This confirms the role of the cereal component as a key factor determining the mechanical behavior of the finished product.

Thus, among the recipes considered, the most optimal in terms of combining physicochemical stability and pronounced brittleness are those containing rice, corn, and wheat. They form a dense, brittle structure with reduced residual moisture and moderate acidity, which increases both consumer appeal and the product's shelf life.

The results from an instrumental assessment of the textural characteristics of grain slices (Table 3) revealed significant variation in key parameters such as breaking force, rigidity, and maximum deformation before failure. These parameters serve as direct indicators of the product's fragility, density, and mechanical stability –properties critical for consumer perception of crunch.

The highest breaking force values (over 3,900 g) were recorded for samples with a predominance of corn, rice, and wheat – specifically, for wheat-rice slices with sea buckthorn (3,922.1 ± 173.5 g) and corn-buckwheat slices with hawthorn (3,811.3 ± 165.2 g) (Table 3). This indicates the formation of a strong and brittle structure capable of withstanding high external pressure until failure. In contrast, the lowest breaking force was observed for the control buckwheat slice (3,054.4 ± 138.2 g), confirming its softer, less brittle consistency. This result is consistent with literature data [13], which report the low mechanical stability of pure buckwheat extrudates due to their loose and weakly bonded structure.

The stiffness index (g/mm), reflecting the resistance to deformation during compression, was also highest for the corn and wheat formulations – up to 460.7 ± 24.0 g/mm (wheat-rice slices) (Table 3). This indicates a dense, uniform structure, characteristic of cereals with a high starch content, which has the ability to gelatinize and form a vesicular matrix. These data confirm the observations of a number of authors who note that corn and wheat starches contribute to the development of a hard texture during extrusion [29–21]. At the same time, the control buckwheat samples again demonstrated minimal values (374.6 ± 18.9 g/mm), indicating lower rigidity and increased plasticity of their texture (Table 3).

An interesting result was revealed for the maximum strain before failure parameter (Tables 3, 6). Unlike force and stiffness, the highest values were recorded for the control sample (9.30 ± 0.46 mm) and the buckwheat-hawthorn slice (9.26 ± 0.42 mm). This indicates high elasticity and softness of these samples – they withstand significant compression before failure. Meanwhile, most formulations with high corn, rice, and wheat content failed at lower strains (8.44–8.71 mm), demonstrating brittleness and low ductility. This effect is also noted in [11], in which buckwheat is characterized as a cereal that forms a less dense and more elastic structure.

Statistical analysis using ANOVA followed by Tukey HSD ($p < 0.05$) confirmed significant differences between slice types for all three parameters. In particular, the breaking force of rice, corn, and wheat-based samples was statistically higher than that of buckwheat and millet-based formulations, as reflected by the different letter labels in Table 3. Thus, formulation changes, including the addition of fruit, influenced the textural characteristics within the acceptable variability range, but the type of cereal component continued to play a major role.

Comparison with previous studies confirms these patterns. For example, study [18] found that crunchiness directly correlates with a sharp peak in compressive force, which is entirely consistent with our observations. However, unlike some sources that describe the effect of fruit additives as weak [19], our study revealed a moderate but consistent increase in stiffness and breaking force with the addition of sea buckthorn or hawthorn, especially when combined with corn and rice. This is probably due to the caramelization of sugars, increased acidity and changes in the viscosity of the medium, which is confirmed by work [20] and other studies on the influence of sugar components on texture.

Thus, instrumental analysis confirmed the high sensitivity of textural parameters to changes in cereal composition. Rice, wheat, and corn produce the strongest and most brittle structures, while buckwheat and millet reduce hardness and crushing force, increasing product ductility. These data allow for informed conclusions regarding the selection of optimal formulations based on the desired textural profile.

The addition of fruit components (sea buckthorn and hawthorn) moderately increased slice brittleness, likely due to the caramelization of natural sugars, vitrification effects, and changes in acidity during extrusion. According to Table 3, this is reflected in increased hardness and crushing force values for samples with fruit additives, particularly for the sea buckthorn formulation (ID 300), which also showed high significance in the PLS model (VIP > 0.9).

Principal component analysis (PCA) and PLS regression allowed us to identify the key variables influencing textural properties. According to Table 5, the largest contributions were made by slice type {300}, breaking force, and stiffness. This emphasizes that fruit additives in combination with certain grains (wheat, buckwheat) have a statistically significant effect on the mechanical behavior of the product.

These results are supported by observations in [20], which show that fruit components, particularly those with higher acid and sugar content, influence the structure of extrudates by changing pH and moisture content. However, unlike [20], which primarily discusses technological aspects, in the present study, the influence of fruit is quantified using PLS models and VIP analysis, representing a new approach to assessing the texture of extruded products.

The behavior of buckwheat slices (ID 100) is interesting. Contrary to expectations, they demonstrated high rigidity and brittleness under certain conditions (Table 3). This is consistent with studies [16, 17], which noted that buckwheat can increase crunchiness in a corn matrix due to its microstructure. However, our study demonstrates for the first time that buckwheat in a single formulation forms a less brittle, more elastic structure, which is further confirmed by the deformation value in Table 6.

The maximum breaking force, as revealed by PLS analysis, is the main variable determining crunchiness (Table 5). This conclusion is consistent with modern data [18], where the peak breaking force is used as an objective indicator of sensory crunchiness. The combined effect of cereal mixtures was also confirmed: samples containing corn, rice, and wheat ({600}, {700}, {800}) exhibited the highest hardness values, consistent with results reported in [19, 22], which indicated corn's ability to form a porous, brittle structure at low moisture content. The textural characteristics, particularly high brittleness and minimal residual deformation upon fracture, can be explained by the favorable component ratio and low residual moisture content, which has also been emphasized in studies on the use of antioxidants and texture stabilizers in the processing of plant products [23].

Thus, a distinctive feature of our work is the comprehensive quantitative assessment of formulation factors, including statistical significance, visualization of the effects of variables (Fig. 5), and confirmation of system stability using control charts (Fig. 4). This approach, in contrast to descriptive studies [13], makes it possible not only to describe the effect but also use the resulting model as a tool for predicting the texture of new recipes, which is consistent with the results obtained in the development of functional bars with fruit components [24, 25].

The practical significance of the study relates to the fact that the constructed regression model and the identified recipe dependences could be used in the design of functional products: extruded snacks with a specified level of crispness, gluten-free bread substitutes for baby and dietary nutrition, and in expanding the range of cereal bars. The resulting dependences allow technologists to predict the texture of new recipes, reduce the costs of experimental selection, and ensure consistent quality during scaling.

Despite our significant results, this study has several limitations that must be considered when interpreting the data and applying the constructed model in practice. First and foremost, the limited sample size should be noted: all experimental data were obtained on nine recipe variants, a result of the laboratory conditions of the study. While this approach is acceptable during the preliminary development stage, it limits the statistical power of the analysis and reduces the generalizability of the results. Future plans include increasing the sample size and repeating the measurements on different production batches and equipment. Another limitation is the lack of external validation of the constructed regression relationships and the partial least squares (PLS) model. Testing the model solely on the original data does not allow for a reliable assessment of its robustness and predictive ability when used on new compositions. Applying the model to independent slice types will be an important step toward assessing its practical applicability.

Furthermore, the study focuses exclusively on instrumental methods of texture analysis, without including sensory or organoleptic assessments. Meanwhile, consumers' perception of crunch and other textural characteristics plays a decisive role in product acceptance. Integrating subjective data will allow for a more precise relationship between physical and mechanical properties and consumer perception.

Finally, the limited range of recipe components studied should be noted: the study examined common cereals and two fruit additives. Further exploration appears promising, with the inclusion of components such as quinoa, amaranth, or inulin, which possess pronounced texture-forming properties and potential for enriching functional foods. Certain aspects of design and interpretation are also subject to critical evaluation, including product microstructure, the instability of some observations, and the influence of specific extrusion parameters. The product microstructure was not examined using scanning or optical microscopy, making it difficult to confirm the observed textural effects at the structural level. The influence of specific extrusion parameters (screw speed, zone temperature, and mixture moisture content) was not analyzed separately, although they may have a critical impact on texture formation and brittleness.

Further research plans to expand the current methodology by incorporating a multivariate design of experiments (DoE), which will allow for the simultaneous consideration of not only recipe parameters but also process conditions such as moisture content, temperature, and pressure. This approach will enable the construction of more comprehensive and realistic models reflecting the relationships between various groups of factors. Of particular interest is the integration of sensory data and digital acoustics, which potentially opens up possibilities for more accurate prediction of perceived crunch. Combining physical and mechanical measurements with consumer perception characteristics will enhance the practical value of the resulting models. Furthermore, the use of 3D printing and digital structural modeling technologies appears to be a promising research direction, potentially laying the foundation for the personalized design of textured products with predetermined consumer characteristics.

Expanding the constructed models to other snack categories – including gluten-free, protein-rich, or nutraceutical-enriched products – will allow the identified relationships to be adapted to a wider range of functional snacks and specialized food systems.

Finally, a key step will be validating the resulting models under industrial-scale conditions, including pilot production lines. This will not only confirm the applicability of the findings in practice but also adapt the models to real-world production conditions, taking into account process limitations and raw material variability.

7. Conclusions

1. The physicochemical and textural characteristics of extruded grain slices with phytoconcentrates have been assessed. All samples met the following standards: moisture content of 7.8–8.5%, acidity of 2.5–2.9°T, and ash content of 0.48–0.55%. The breaking force varied from 3054 g (buckwheat, ≈ 29 N) to 3922 g (wheat + rice, ≈ 38 N), with corn and rice producing a more brittle structure (deformation ≤ 10%), while buckwheat and millet contributed to plasticity (deformation > 15%).

2. Statistical analyses (ANOVA, Tukey HSD, PLS/VIP) confirmed significant differences between the slice types. Up to 70% of the variation in hardness is explained by the type of cereal base, while fruit additives (sea buckthorn, hawthorn) make a modifying contribution of 10–15%, increasing brittleness through sugar caramelization and pH changes.

3. A mathematical model was constructed ($R^2 = 0.69$; Adj. $R^2 = 0.64$; $p = 0.0056$; $R^2Y = 0.98$), which allowed us to identify quantitative relationships between composition and textural properties. VIP analysis and PCA revealed that corn, rice, and millet contribute the most to the variability in textural characteristics, while buckwheat and hawthorn act as mitigating factors. X-ray and Moving R control charts

confirmed the stability of the technological process, with the exception of samples containing sea buckthorn.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Funding

Experiments were conducted as a part of project AP19577363 funded by the Ministry of Education and Science of the Republic of Kazakhstan “Development of technology of functional extrusion foods using wild plants of Republic of Kazakhstan”.

Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Acknowledgments

The project team expresses its deep gratitude to the management of the Almaty Technological University for their support and to the Research Institute of Food Safety for their high-quality consulting and assistance in conducting the analyses.

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