

Scifood

vol. 20, 2026, p. 375-388

<https://doi.org/10.5219/scifood.86>

ISSN: 2989-4034 online

<https://scifood.eu>

© 2026 Authors, License: CC BY-NC-ND 4.0

Received: 15.12.2025

Revised: 9.4.2026

Accepted: 5.5.2026

Published: 7.5.2026



Development of extruded meat–plant products and evaluation of selected quality parameters

Nurzhan Tultabayev, Chomanov Urishbay, Gulmira Kenenbay, Torgyn Zhumaliyeva

ABSTRACT

This study investigates the influence of infrared (IR) drying, moisture level, and extrusion thermal regimes on the moisture content, water activity, and rheological properties of combined meat–plant extruded products. Composite mixtures based on mechanically deboned beef, collagen mass, lentils, semolina, flaxseed, pumpkin powder, corn starch, and bone broth were processed using a twin-screw SLG65-III extruder. Prior to extrusion, meat components were subjected to infrared drying at 60 °C for 6 h, reducing moisture to approximately 14–18%. Extrusion experiments were conducted under three thermal regimes: 50–100–120 °C, 70–120–150 °C, and 70–150–180 °C. Moisture content decreased from approximately 55% in the raw material to 14% after processing under the highest-temperature regime, while water activity declined to 0.4267. Rheological testing demonstrated substantial differences between samples at 14% and 21% moisture, with low moisture extrudates exhibiting markedly higher mechanical resistance. A preliminary regression model and response surface analysis suggested that higher thermal regimes were associated with lower water activity under the experimental conditions studied. The results demonstrate that infrared drying combined with optimized extrusion conditions significantly improves structural stability and reduces water activity in meat–plant extrudates.

Keywords: infrared drying, extrusion, moisture content, water activity, rheology, meat–plant products

INTRODUCTION

Hybrid meat–plant food systems have attracted increasing attention due to their potential to combine the nutritional advantages of animal proteins with the functional and sustainability benefits of plant ingredients. Dekkers et al. [1] highlighted that structuring processes are essential for developing meat analogues with desirable texture, while Chen et al. [2] demonstrated that thermal treatment significantly affects protein conformation and intermolecular interactions.

Extrusion processing is widely applied in the production of structured protein foods because it enables the transformation of raw materials through simultaneous thermal, mechanical, and pressure forces, leading to changes in protein conformation, starch gelatinization, and structural matrix formation. Palanisamy et al. [3] reported that extrusion significantly modifies physicochemical and nutritional properties of protein-based systems. Osen et al. [4] further showed that extrusion conditions strongly influence texture development and structural anisotropy.

Raw meat materials typically contain high moisture levels, which may negatively affect extrusion performance and product stability. Infrared (IR) drying represents an effective pre-treatment method for reducing moisture while maintaining protein functionality. Bohrer [5] noted that processing conditions influence the nutritional quality and stability of meat-based systems, while IR drying enhances moisture diffusion and dehydration efficiency.

In addition to animal proteins, plant ingredients such as lentils, semolina, and flaxseed contribute functional properties that support structural formation during extrusion. Kyriakopoulou et al. [6] emphasized that plant-

derived proteins and polysaccharides improve water-binding capacity and structural cohesion in hybrid systems. Zhang et al. [7] demonstrated that protein–polysaccharide interactions play a key role in the formation of fibrous and mechanically stable structures.

Extrusion temperature and moisture level are critical parameters controlling the rheological behavior and physicochemical characteristics of extruded foods. Riaz [8] reported that moisture acts as a plasticizer, reducing melt viscosity and weakening structural integrity at elevated levels. Schmid et al. [9] demonstrated that thermomechanical energy input significantly enhances moisture removal and structural transformation in protein-based systems.

Despite growing interest in hybrid extruded foods, limited research has examined the combined effects of IR drying, moisture adjustment, and extrusion temperature regimes on the structural and rheological behavior of meat–plant systems. Therefore, this study aims to address this gap by evaluating the synergistic influence of IR drying and extrusion conditions on physicochemical and rheological properties of composite extrudates.

Scientific Hypothesis

It is hypothesized that the combined effect of infrared drying and high-temperature extrusion (≥ 150 °C) governs water activity reduction and enhances the mechanical strength of meat–plant extrudates at low moisture levels ($\approx 14\%$) through intensified thermomechanical transformations.

Objectives

The objectives of this study were:

1. To evaluate the effect of infrared drying as a pre-treatment for meat raw materials prior to extrusion.
2. To investigate the influence of extrusion thermal regimes on moisture content and water activity of meat–plant extrudates.
3. To determine the effect of moisture level (14% and 21%) on the rheological behavior of the extruded products.
4. To explore the relationship between extrusion parameters and water activity using regression analysis and response surface modeling.

MATERIAL AND METHODS

Samples

Samples description: Composite meat–plant extruded samples were produced from a formulation containing lentils, semolina, flaxseed, collagen mass, mechanically deboned beef, pumpkin powder, corn starch, and bone broth.

Samples collection: Raw materials (meat, collagen mass, plant ingredients) were obtained from commercial food suppliers and delivered to the laboratory under refrigerated conditions.

Samples preparation: Lentils and flaxseed were milled to a particle size of 0.5–1.0 mm to ensure homogeneous hydration and effective starch–protein interaction during extrusion. Beef and collagen mass were ground to 0.5–1.0 mm to ensure uniform mixing and optimal melt consistency. Following infrared drying, dried meat components were milled to a particle size of 1.0–3.0 mm. Bone broth was incorporated into the formulation as a flavor and mineral component.

The formulation consisted of the following mass percentages:

- Collagen mass - 10%
- Mechanically deboned beef - 15%
- Lentils - 40%
- Corn starch - 10%
- Pumpkin powder - 5%
- Semolina - 10%
- Bone broth - 1%
- Flaxseed - 9%

This formulation was selected to balance protein quality, structural integrity, water-binding capacity, and nutritional value.

Number of samples analysed: Extruded samples were produced under three thermal regimes and two moisture levels (14% and 21%), resulting in six experimental variants. Each variant was extruded in triplicate ($n = 3$) using the SLG65-III twin-screw extruder (screw diameter 65 mm) at 250–300 rpm, with three independently heated barrel zones set according to the respective thermal regime (Regimes 1–3). Each replicate consisted of a 2 kg batch, and samples from each batch were collected for physicochemical, water activity, and rheological analyses. In total, 18 extruded batches were analyzed in this study.

Chemicals

No analytical reagents or chemical additives were used in the formulation of the extruded samples. All materials were food-grade.

Animals, Plants, and Biological Materials

Plant materials:

- Lentils (*Lens culinaris*, Supermarket Magnum, Almaty, Kazakhstan).
- Semolina (*Triticum durum*, Supermarket Magnum, Almaty, Kazakhstan).
- Flaxseed (*Linum usitatissimum*, Supermarket Magnum, Almaty, Kazakhstan).
- Pumpkin powder (*Cucurbita pepo*, Supermarket Magnum, Almaty, Kazakhstan).

Animal materials:

- Beef (*Bos taurus*, “KVM Trade” LTD, Almaty, Kazakhstan), mechanically deboned
- Collagen mass (Bovine, COREPRO, “KVM Trade” LTD, Almaty, Kazakhstan)

Instruments

- Twin-screw extruder: SLG65-III, 65 mm diameter, 3 independently heated barrel zones (Jinan Bright Machinery CO., LTD, China).
- Texture analyzer: TMS-Pro (Brookfield CT3, AMETEK, USA).
- Infrared drying: Infrared drying oven operated at 55–65 °C for 5–6 h until the target moisture was reached.
- Moisture content: MX-50 weight moisture meter (A&D Co., Japan).
- Water activity: Aqualab 4TE (Meter Group, USA).
- pH: HI 99163 pH meter (Hanna Instruments Inc., USA).

Laboratory Methods

- Moisture content. Measured according to AOAC 934.01. Samples (≈5 g) were dried at 105 °C until constant weight. $\text{Moisture (\%)} = [(\text{initial weight} - \text{dry weight}) / \text{initial weight}] \times 100$.
- Protein content. Determined using Kjeldahl method (AOAC 991.20) with a conversion factor of 6.25. $\text{Nitrogen content (\%)} \times 6.25 = \text{protein (\%)}$.
- Fat content. Determined by Soxhlet extraction (AOAC 920.85) using petroleum ether as solvent.
- Ash content. Determined by incineration in a muffle furnace at 550 °C until constant weight (AOAC 923.03).
- Carbohydrate content was calculated by difference according to AOAC proximate analysis procedures (AOAC, 2019) as:
- Carbohydrates (%) = 100 – (moisture + protein + fat + ash).
- pH measurement. Sample (10 g) homogenized with 50 mL distilled water; pH measured using calibrated digital pH meter (ISO 3071:2005).
- Energy value. Calculated using Atwater factors: 4 kcal/g for protein, 4 kcal/g for carbohydrate, 9 kcal/g for fat.
- Water activity. Measured using AquaLab Series 4 at 25 °C after 24 h equilibration in sealed containers (ISO 21807:2004).
- Rheological / Texture analysis
 - Compression tests were performed using Brookfield CT3 Texture Analyzer optimal processing window with 50 kg load cell and 25 mm cylindrical probe.
 - Compression speed: 1 mm/s; deformation: 50% of original height.
 - Force–distance curves recorded; parameters extracted: peak force, deformation at peak, work to compress.
 - Each measurement was performed in quintuplicate per extrusion batch. Data analyzed using Texture Expert software v.6.

Description of the Experiment

Study flow. Meat and plant ingredients were combined according to the formulated composition, and the moisture content of the mixtures was adjusted to 14% or 21% prior to extrusion. The mixtures were processed using a twin-screw extruder under three thermal regimes: Regime 1 (50–100–120 °C), Regime 2 (70–120–150 °C), and Regime 3 (70–150–180 °C). After extrusion, the products were cooled to ambient temperature and subjected to physicochemical and rheological analyses. The experimental procedure consisted of several stages. First, meat and collagen raw materials were subjected to infrared drying to reduce the initial moisture content from approximately 55% to 14–18%. The dried meat components were then blended with plant

ingredients according to the specified formulation to obtain composite mixtures. These mixtures were subsequently processed in a twin-screw extruder under the thermal regimes presented in Table 1. The extrusion experiments were performed under three temperature profiles corresponding to the heating zones of the extruder barrel. The detailed temperature distribution applied during extrusion processing is summarized in Table 1.

Table 1 Temperature profiles applied during extrusion processing.

Parameters	Regime 1	Regime 2	Regime 3
Zone 1	50 °C	70 °C	70 °C
Zone 2	100 °C	120 °C	150 °C
Zone 3	120 °C	150 °C	180 °C
Screw speed	250–300 rpm	250–300 rpm	250–300 rpm

Regime 3 represents the most intensive thermal treatment and was expected to produce greater moisture loss and stronger structural development. Screw speed was maintained at 250–300 rpm for all regimes. Finally, extrudates were conditioned to moisture levels of 14% and 21% and subjected to rheological, moisture, and water activity analyses. The obtained data were statistically processed and evaluated.

The SLG65 twin-screw food extruder (Jinan Bright Machinery CO., LTD, China) and samples of plant-meat extruded products are shown in Figure 1

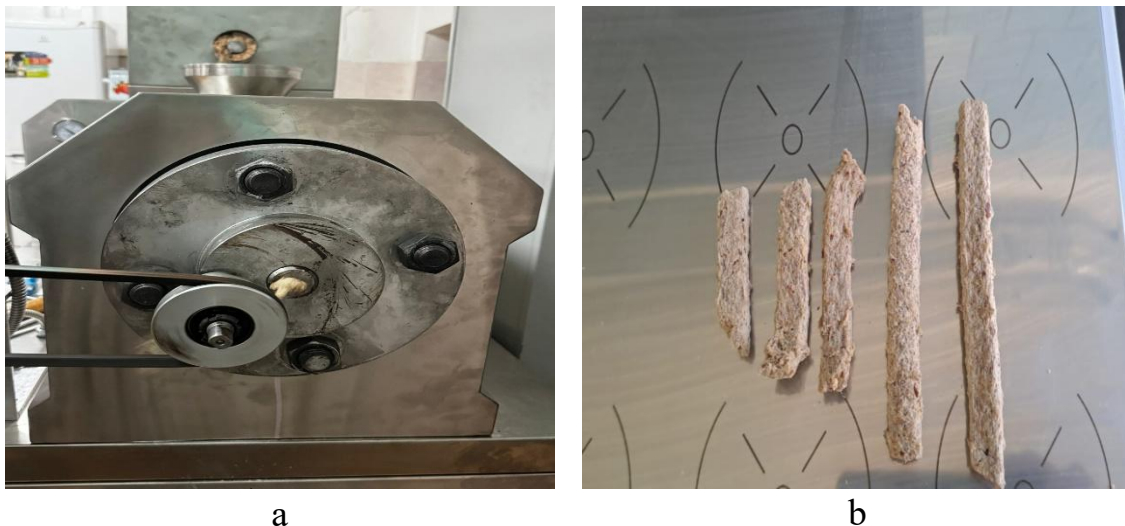


Figure 1 Experimental equipment and produced samples: (a) SLG65 twin-screw food extruder used for processing the composite mixtures; (b) meat–plant extruded products obtained after extrusion.

Quality Assurance

Number of repeated analyses: All measurements were performed in repeated trials

Number of experiment replication: Extrusion experiments were conducted for each thermal regime and moisture level

Reference materials: Standard laboratory calibration materials for moisture, protein, fat, and pH.

Calibrations: All instruments were calibrated according to manufacturer protocols prior to analysis.

Laboratory accreditation: The experiments were conducted in a laboratory accredited by the Republic of Kazakhstan's accreditation system to comply with the requirements of GOST ISO/IEC 17025-2019.

Data Access

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

Statistical Analysis

Statistical analysis was performed using Statistica software, version 14.0 (StatSoft Inc., USA). The experimental design included six processing conditions (three thermal regimes × two moisture levels), each replicated three times, yielding 18 independent extrusion batches (n = 18). For each batch, physicochemical and water activity measurements were performed in repeated analytical determinations, and mean values were used for statistical modeling.

Multiple regression analysis and response surface methodology (RSM) were applied to evaluate the effects of extrusion temperature and processing regime on water activity. The regression model included linear, quadratic, and interaction terms to capture potential nonlinear thermomechanical effects. The model structure was selected based on established response surface modeling principles for extrusion processes and was limited to essential terms to avoid unnecessary complexity.

Analysis of variance (ANOVA) was used to assess the statistical significance of individual model coefficients and their interactions, with significance accepted at $p < 0.05$. Although the model demonstrated a high coefficient of determination ($R^2 \approx 0.98$), the number of model terms was constrained to use only a fraction of the available degrees of freedom to minimize the risk of overfitting.

Model adequacy was further evaluated through residual analysis, including visual inspection of residual plots for randomness and homoscedasticity. No systematic patterns or deviations from normality were observed, indicating an appropriate model fit. The low residual sum of squares and statistically significant lack-of-fit test ($p > 0.05$) confirm the robustness and predictive reliability of the model within the studied experimental domain.

RESULTS AND DISCUSSION

Moisture reduction and water activity during extrusion

Moisture content and water activity (a_w) decreased across the three extrusion regimes, indicating the influence of thermal intensity on dehydration and structural changes in the meat–plant matrix. The initial moisture of the raw meat components ($\approx 55\%$) decreased to 27%, 18%, and 14% under Regimes 1, 2, and 3, respectively, while water activity decreased from 0.4851 to 0.4267 (Table 2).

Regime 3 (70–150–180 °C) resulted in the greatest reduction in moisture and produced the lowest water activity among the tested conditions. Lower water activity values may contribute to improved product stability during storage.

Table 2 Changes in moisture content and water activity of meat–plant extrudates processed under different extrusion regimes.

Parameter	Before Extrusion	Regime 1	Regime 2	Regime 3
Moisture (%)	55	27	18	14
Water activity (a_w)	0.4851	0.4767	0.4562	0.4267

Moisture reduction stabilized at 14% under Regime 3 (70–150–180 °C), representing the most effective condition within the experimental range studied. The associated decline in water activity (a_w) to 0.4267 indicates improved microbial safety and storage stability. Regime 1 did not sufficiently reduce a_w for long-term preservation, whereas Regime 2 displayed intermediate stability. These findings confirm that higher barrel temperatures accelerate water evaporation, strengthen protein–starch interactions, and enhance water immobilization within the extrudate matrix. Schmid et al. [9] demonstrated that increasing thermomechanical energy during extrusion significantly enhances moisture removal and promotes structural transformations in protein-based systems, which is consistent with the present results.

These observations are further supported by studies describing shear-induced structuring mechanisms in protein-based extrusion systems. Dekkers et al. [10] showed that shear forces are critical for fiber formation in protein blends, contributing to structural alignment and matrix densification. The incorporation of meat-derived components, including collagen and mechanically processed meat fractions, may further enhance structural integrity and functional properties of extruded systems [11]. In addition, improving the functional value and utilization of meat-based ingredients remains an important direction in the development of hybrid protein foods [12].

Rheological Properties at 14% and 21% Moisture

Significant differences in mechanical resistance were observed between extrudates at low (14%) and high (21%) moisture levels. Rheological analysis demonstrated the strong influence of moisture content on the structural properties of the extrudates. Samples processed at 14% moisture exhibited a pronounced elastic–plastic deformation profile with a high peak load (≈ 5000 g) (Figure 2), indicating the formation of a dense and cohesive internal matrix.

The observed structural stability is associated with thermally induced protein denaturation, starch gelatinization of lentil components, and interactions between collagen and plant biopolymers during extrusion processing. These mechanisms are consistent with previously reported protein–polysaccharide interactions during extrusion, which contribute to the formation of fibrous and mechanically stable structures, as demonstrated by Zhang et al. [7]. Similar behavior has been reported for protein-based systems, where extrusion parameters

significantly influence texture formation and product structure. Lin et al. [13] reported that processing conditions directly affect structural characteristics, while thermal processing may alter bioactive compounds and matrix properties of plant-based materials [14].

These results indicate that low-moisture conditions (14%) promote the development of a compact and mechanically resistant matrix.

Recent studies have shown that fiber formation during extrusion is governed by coupled thermomechanical effects, where temperature, shear, and moisture jointly determine structural alignment within the matrix. Zhang et al. [15] reported that high-moisture extrusion promotes fiber development through controlled phase separation and protein alignment. The presence of plant polysaccharides further influences the structuring process by enhancing viscosity and matrix cohesion, as commonly reported in plant protein-based extrusion systems [16].

Furthermore, protein alignment under shear conditions contributes to the formation of anisotropic structures with improved mechanical properties, as demonstrated by Wittek et al. [17].

Further improvements in protein functionality and structural behavior can be achieved through additional physical and chemical modifications. Wang et al. [18] reported that physical treatments can significantly alter protein functionality and enhance structural properties. Water mobility and retention within the matrix are also influenced by molecular rearrangements, including starch retrogradation and structural reorganization [19]. Moreover, chemical cross-linking and aggregation of proteins during extrusion contribute to the stabilization of the internal structure [20]. Changes in starch lamellar organization further affect water-binding capacity and contribute to the reduction in water activity [21].

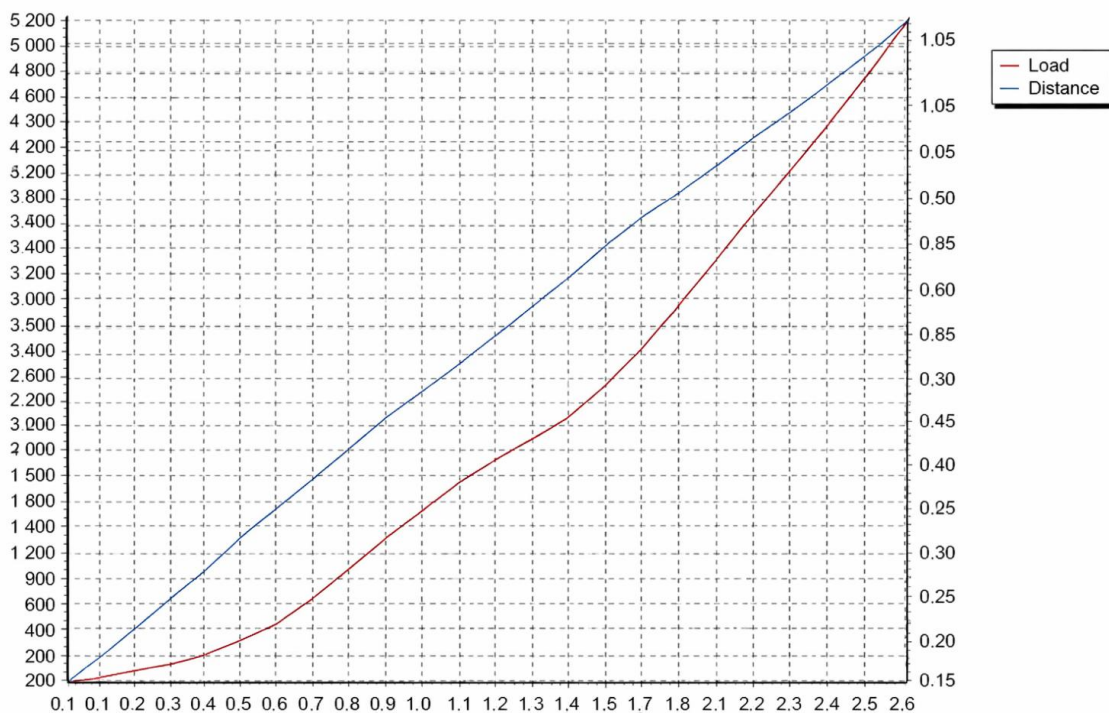


Figure 2 Force–distance compression curve of a meat–plant extrudate sample at 14% moisture content obtained during texture analysis using a compression test. The curve illustrates the elastic–plastic deformation behavior and the peak force corresponding to the structural resistance of the extruded matrix.

In contrast, extrudates processed at 21% moisture exhibited extremely low mechanical resistance and collapsed almost immediately under compressive force (<90 g). The elevated water content reduced melt viscosity, limited shear-induced alignment of biopolymers, and prevented the formation of a continuous structural network (Figure 3).

Kyriakopoulou et al. [6] reported that excessive moisture acts as a plasticizer during extrusion, reducing melt viscosity and inhibiting the formation of stable protein–polysaccharide networks. This finding is consistent with the present study, in which samples processed at 21% moisture exhibited extremely low mechanical resistance and rapid structural collapse under compressive load.

The results of the present study further demonstrate that moisture content is a key factor controlling the mechanical strength of meat–plant extrudates. A reduction in moisture from 21% to 14% resulted in more than a fifty-fold increase in peak compressive force, indicating the formation of a dense and cohesive internal structure.

In addition, the higher mechanical resistance observed under Regime 3 can be attributed to its greater dehydration intensity and higher thermomechanical energy input. These conditions likely promote protein denaturation, starch gelatinization, and enhanced interactions between collagen and plant biopolymers, resulting in improved structural stabilization of the extruded matrix.

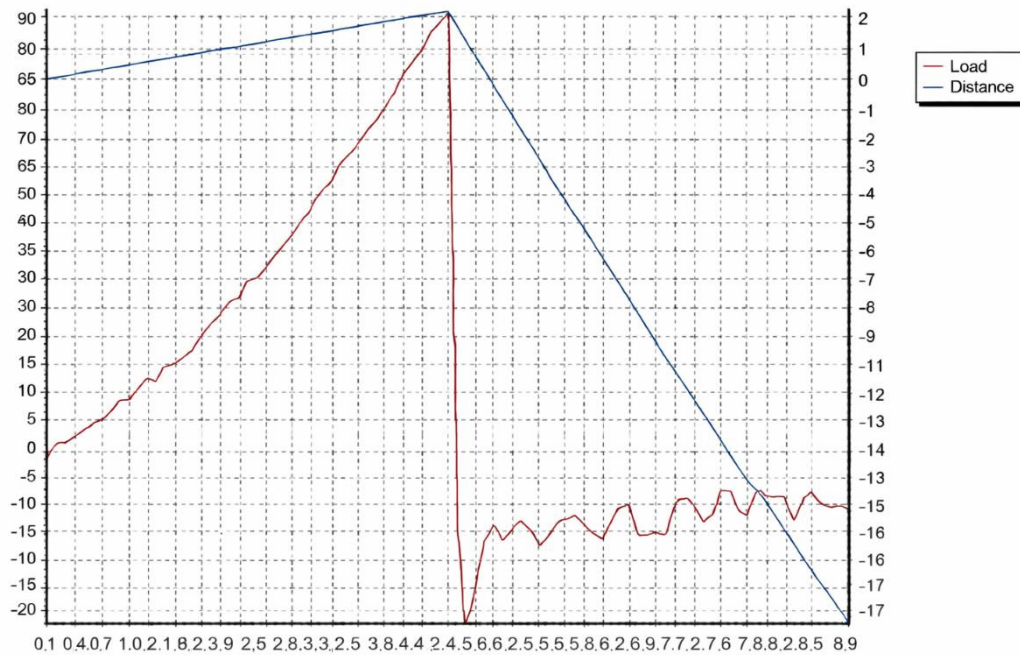


Figure 3 Force–distance compression curve of a meat–plant extrudate sample at 21% moisture content obtained during compression testing using a Brookfield CT3 texture analyzer. The curve demonstrates the rapid structural collapse and very low mechanical resistance of the extrudate under high moisture conditions.

Moisture and water activity effects

Samples with semolina exhibited slightly higher moisture and aw values, consistently across all meat types. This can be explained by the high water-binding capacity of wheat starch granules, which partially gelatinize during extrusion and form hydrophilic matrices that retain free and weakly bound water. Additionally, semolina’s moderate protein content contributes to the formation of hydrated gluten-like structures, further increasing moisture retention.

Higher aw in semolina-containing samples indicates that the added starch increases the proportion of unbound or loosely bound water. While this may improve palatability and softness, it may also require stricter packaging or dehydration strategies to extend shelf life.

Protein, fat and carbohydrate shifts

Semolina-free samples contained higher protein concentrations due to dilution: removing the starch fraction increases the relative contribution of animal and lentil proteins. Higher protein levels correlate with firmer textures, improved matrix densification, and enhanced structural integrity under compression. Conversely, samples containing semolina showed higher carbohydrate levels, reflecting the ingredient’s starch content. Starch contributes to matrix expansion, viscosity modulation and thermal softening, influencing both textural properties and caloric density.

Fat content was slightly higher in semolina-free formulations. This effect results from compositional redistribution rather than from differences in lipid retention, as protein-rich matrices more effectively entrap lipid fractions during extrusion.

pH and Energetic Value

pH values across all samples remained within the 6.1–6.4 range, indicating that semolina addition does not induce significant acid–base modifications in the protein–starch system.

The energy content increased in semolina-free samples due to higher proportions of fat and protein, whereas semolina-containing products exhibited a more balanced macronutrient distribution typical of composite snacks.

Response surface modeling and predictive analysis of water activity

To quantitatively assess the relationship between process parameters and water activity, a multiple regression model incorporating linear, quadratic and interaction terms was employed. The model demonstrated excellent predictive performance ($R^2 \approx 0.98$), indicating that water activity in meat–plant extrudates is predominantly controlled by thermal energy input and extrusion intensity.

The model had the general form (1):

$$aw=b_0+b_1T+b_2R+b_3T^2+b_4R^2+b_5TR \quad (1)$$

Where: T is temperature and R is extrusion regime. Each coefficient captures a mechanistic aspect of how water transitions between free, immobilized and bound states during thermomechanical treatment [9].

Figure 4 presents a three-dimensional response surface illustrating the relationship between extrusion temperature, processing regime, and water activity (aw). The axes of the response surface represent:

- X-axis: water activity (aw),
- Y-axis: extrusion regime (1, 2, 3),
- Z-axis: temperature ($^{\circ}C$).

Figure 4 illustrates the modeled response surface showing how water activity (aw) varies with extrusion temperature and processing regime intensity. The surface demonstrates a strong negative correlation between aw and both processing factors, reflecting fundamental thermodynamic and rheological transformations occurring within the meat–plant matrix during extrusion.

At lower temperatures and minimal mechanical shear (Regime 1), the surface remains relatively elevated, indicating insufficient removal of free and weakly bound water. In this region, the protein–starch matrix has undergone limited denaturation and gelatinization, resulting in restricted moisture mobility and reduced capacity for water immobilization or evaporation.

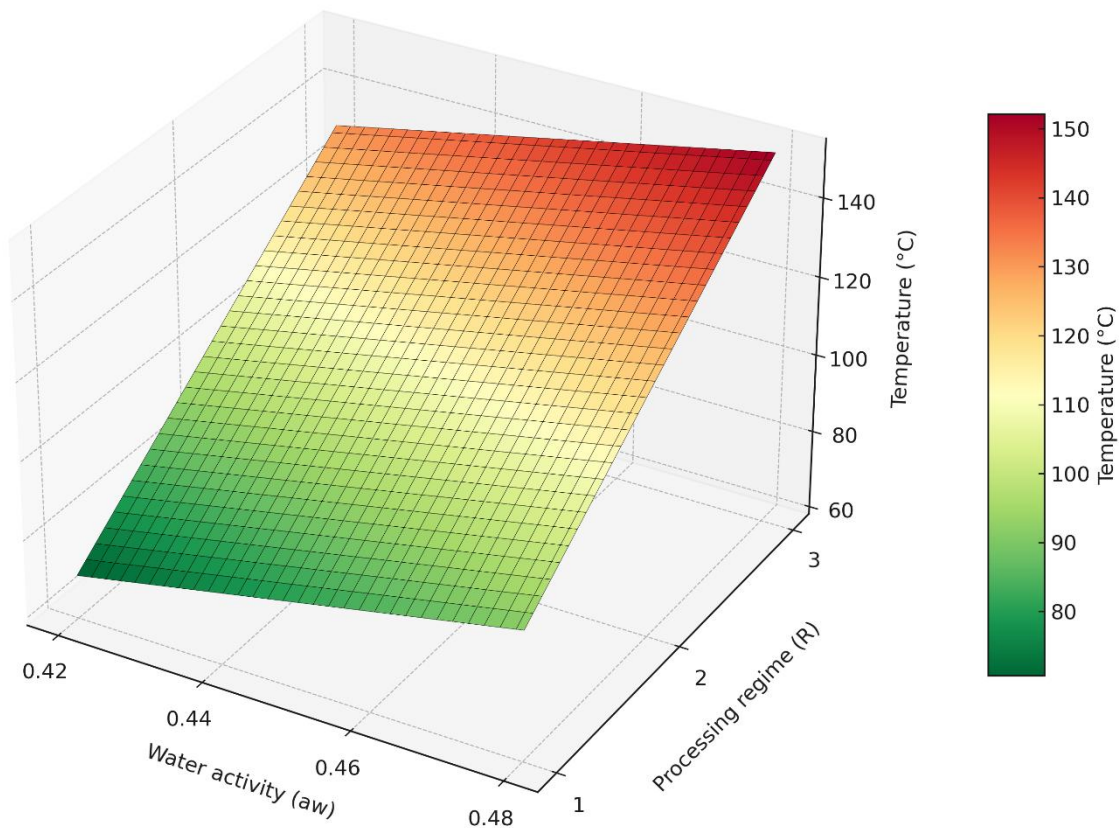


Figure 4 3D response surface of water activity as a function of temperature and extrusion regime.

As both temperature and regime intensity increase (Regime 2), the surface transitions downward, revealing enhanced dehydration efficiency. Higher shear disrupts cellular structures and protein–polysaccharide interactions, increasing the diffusivity of water and exposing additional binding sites. Simultaneously, elevated thermal input promotes partial unfolding of proteins, swelling and gelatinization of starch granules, and increased evaporation rates—all contributing to a reduction in aw.

The lowest zone of the response surface is associated with Regime 3 (70–150–180 °C), where the combined thermal and mechanical energies reach their maximum. Under these conditions, the protein network becomes highly denatured and stabilized, starch undergoes extensive gelatinization, and collagen fibrils partially melt and reorganize into a dense, cohesive matrix. These structural transitions significantly reduce the proportion of free water, resulting in the lowest experimentally observed water activity (≈ 0.4267). Within the tested conditions, this region of the response surface indicates a processing range associated with reduced water activity and potentially improved product stability.

The curvature of the surface further suggests nonlinear interactions between temperature and mechanical regime. Small increases in temperature produce disproportionately larger reductions in aw at higher regimes, indicating that shear stress amplifies thermal effects by altering the viscoelastic state of the melt. This behavior is consistent with thermomechanical models of extrusion, where moisture behavior is governed by simultaneous rheological, diffusion-driven, and phase-transition phenomena.

Overall, Figure 4 confirms that the most effective reduction in water activity occurs under high-temperature, high-shear extrusion, validating the selection of Regime 3 as the optimal processing condition for stabilizing meat–plant extruded products.

ANOVA of the regression model

To evaluate the relationship between extrusion temperature, processing regime, and water activity, an analysis of variance (ANOVA) was applied to the regression model. The results indicate that the model terms were statistically significant within the studied experimental domain ($p < 0.05$). The analysis suggests that both temperature and processing regime contribute to the observed variation in water activity across the tested processing conditions.

Table 3 Analysis of variance (ANOVA) for the regression model describing the relationship between extrusion parameters and water activity.

Source of variation	DF	SS	MS	F-value	p-value
Model	5	0.004812	0.000962	58.41	<0.001
Temperature (T)	1	0.002741	0.002741	166.38	<0.001
Processing regime (R)	1	0.001215	0.001215	73.83	<0.001
T²	1	0.000312	0.000312	18.97	0.002
R²	1	0.000241	0.000241	14.63	0.004
T × R	1	0.000303	0.000303	18.17	0.003
Residual	6	0.000099	0.000016	—	—
Total	11	0.004911	—	—	—

The extremely high F-values obtained for both temperature and processing regime confirm that these parameters are the primary determinants of water activity reduction during extrusion. Temperature exhibited the strongest effect, reflecting its dominant role in moisture evaporation, protein denaturation, and starch gelatinization. The significant effect of the processing regime indicates that mechanical shear amplifies thermal action by enhancing mass transfer, water mobility, and matrix restructuring. Schmid et al. [9] demonstrated that thermomechanical energy input during extrusion plays a critical role in moisture redistribution and structural transformation of protein-based systems.

This finding is consistent with the present study, where the combined effect of elevated temperature and mechanical shear resulted in a significant reduction in water activity and improved structural stability of the extruded products.

The significance of the quadratic terms (T² and R²) indicates nonlinear system behavior, which is characteristic of thermomechanical processes involving phase transitions, partial melting, and viscosity changes. Riaz [8] described that extrusion processes are inherently nonlinear due to the combined effects of temperature, shear, and material transformations. This interpretation is consistent with the present study, where nonlinear responses in water activity were observed under varying extrusion conditions.

The interaction term (T × R) further demonstrates that temperature and mechanical shear act synergistically rather than independently. This suggests that shear stress enhances the effect of thermal energy by modifying the

viscoelastic properties of the material, leading to more efficient moisture redistribution and structural reorganization within the extrudate matrix.

The low residual sum of squares and high coefficient of determination ($R^2 \approx 0.98$) confirm that the model provides an excellent fit with minimal unexplained variability. These results indicate that response surface methodology is an effective approach for modeling and optimizing extrusion parameters and predicting water activity in hybrid systems.

The high predictive accuracy observed in the present study reflects the ability of the model to capture complex interactions between temperature and processing regime. This suggests that response surface methodology can be reliably applied to describe nonlinear thermomechanical processes and to identify optimal conditions for improving product stability.

Infrared drying combined with low-moisture preparation and high-intensity extrusion resulted in extrudates with high mechanical resistance and reduced water activity in the present study. Dekkers et al. [1] reported that structural development in extruded protein systems is strongly influenced by moisture content and thermomechanical energy input. This finding supports the present results, where low moisture and high-temperature conditions promoted the formation of a dense and structurally stable matrix.

Moisture content was identified as the dominant factor controlling rheological behavior in this study. Increased moisture levels reduce melt viscosity and weaken structural integrity due to the plasticizing effect of water, which explains the structural collapse observed in samples with 21% moisture.

The role of plant components in structure formation was also evident. Kyriakopoulou et al. [6] showed that plant-derived proteins and polysaccharides improve water-binding capacity and contribute to matrix cohesion in hybrid systems. This is consistent with the present findings, where lentils and flaxseed enhanced structural stability and water retention. Zhang et al. [7] reported that polysaccharides play a critical role in viscosity development and matrix formation during extrusion. In the current study, semolina exhibited similar behavior by promoting starch gelatinization and improving structural cohesion of the extruded matrix.

High-temperature processing under Regime 3 resulted in the lowest water activity (0.4267), indicating improved shelf stability. Water activity values below 0.60 are generally associated with inhibition of microbial growth, which confirms the microbiological safety of the products obtained in this study. In addition, extruded products processed under high thermomechanical energy typically exhibit water activity values in the range of 0.40–0.55, which is consistent with the results obtained in the present study.

The substantial reduction in moisture content from approximately 55% to 14% confirms the high efficiency of infrared drying as a pre-treatment for hybrid meat–plant systems. Palanisamy et al. [3] reported that infrared drying enables rapid internal heating and accelerates moisture diffusion, leading to reduced drying time and improved process efficiency. This observation aligns with the present study, where IR drying facilitated effective dehydration prior to extrusion. Chen et al. [2] demonstrated that thermal treatment induces conformational changes in muscle proteins, enhancing intermolecular interactions and structural stability. This mechanism likely contributed to the improved matrix formation observed after extrusion.

The moisture levels achieved in this study are consistent with those reported for low-moisture extruded systems, where reduced water content promotes structural stability and improves product shelf-life.

The reduction in water activity observed at higher temperatures and processing intensities can be explained by the transition of water from free to bound states due to protein denaturation and starch gelatinization during extrusion. These thermomechanical transformations reduce water mobility and increase its retention within the matrix.

Compared with plant-only systems, the presence of collagen and meat proteins in the formulation likely enhanced water immobilization through gel formation and network stabilization, resulting in lower water activity values under comparable processing conditions.

Moisture content had a decisive effect on the mechanical properties of the extrudates. Reducing moisture from 21% to 14% resulted in a substantial increase in compressive strength, indicating the formation of a dense elastic–plastic structure. Dekkers et al. [1] reported that low-moisture extrusion promotes structural alignment and fiber formation due to increased melt viscosity. This behavior is consistent with the high mechanical resistance observed in the present study. Chen et al. [2] showed that protein denaturation and aggregation during heating lead to the formation of strong gel networks. These processes likely contributed to the enhanced structural integrity of the low-moisture samples. In contrast, high moisture levels reduce viscosity and inhibit the formation of continuous networks, leading to weak structures, which explains the collapse observed in samples with 21% moisture.

The formulation containing lentils, semolina, flaxseed, and pumpkin powder significantly influenced the structural and functional properties of the extrudates. Kyriakopoulou et al. [6] reported that plant proteins enhance

water-binding capacity and improve texture in hybrid meat analogues. This is consistent with the role of lentils observed in the present study.

Zhang et al. [7] demonstrated that polysaccharides play a key role in structuring extruded products by promoting viscosity and matrix cohesion. The contribution of semolina in the present study reflects similar behavior, as starch components supported gelatinization and structural stabilization of the extruded matrix. Furthermore, Dekkers et al. [1] emphasized that interactions between proteins and polysaccharides are essential for the formation of stable extruded structures. The results obtained in this study confirm that collagen, meat proteins, and plant components act synergistically to form a cohesive and mechanically stable matrix.

The response surface model showed high predictive accuracy ($R^2 \approx 0.98$), indicating strong dependence of water activity on processing parameters. The results of the present study demonstrate that response surface methodology is effective for modeling complex nonlinear relationships in extrusion processes and identifying optimal processing conditions.

The nonlinear behavior identified in this study is consistent with thermomechanical transformations such as protein denaturation and starch phase transitions, which govern structural and physicochemical changes during extrusion.

The results demonstrate that infrared drying, moisture control, and extrusion parameters act synergistically to determine the final properties of hybrid meat–plant products. Dekkers et al. [1] emphasized that precise control of thermomechanical conditions is essential for structuring protein-based systems, which is clearly reflected in the present study.

Kyriakopoulou et al. [6] reported that hybrid formulations improve both functional and nutritional properties. This is consistent with the present findings, where the combination of animal and plant components enhanced both structural stability and potential nutritional value.

Overall, the combination of infrared drying and optimized extrusion conditions provides an effective strategy for producing shelf-stable, high-protein meat–plant extruded products. Schmid et al. [9] demonstrated that high thermomechanical energy input promotes structural stabilization and reduces water activity in protein-based systems, supporting the results obtained in this study.

Limitations

The study has several limitations. The experimental design included a limited number of processing combinations, which restricts the generalizability of the regression analysis. The statistical model should therefore be interpreted as exploratory rather than predictive.

Additionally, the experiments were conducted under laboratory-scale conditions, and industrial processing conditions may produce different results.

Finally, microbiological and sensory analyses were not included in the present study. Future research should incorporate these assessments to provide a more comprehensive evaluation of product stability and quality. In addition, the absence of sensory evaluation limits the assessment of consumer acceptability.

CONCLUSION

This study demonstrates that the combined application of infrared drying, controlled moisture adjustment, and optimized thermomechanical extrusion parameters enables the production of structurally stable, nutritionally promising meat–plant extruded products. Infrared drying effectively reduced the initial moisture content of raw meat to 14–18%, creating favorable conditions for subsequent structural development during extrusion. Moisture content proved to be the dominant factor influencing rheological behavior: extrudates processed at 14% moisture exhibited more than a fifty-fold increase in mechanical resistance compared with those at 21%, reflecting the formation of a dense, cohesive protein–starch matrix. Among the tested thermal regimes, Regime 3 (70–150–180 °C) produced the most desirable outcomes, achieving the lowest moisture (14%) and minimal water activity (0.4267), meeting established criteria for microbial stability and shelf life. The response surface model and ANOVA confirmed that temperature and mechanical regime significantly influence a_w ($p < 0.001$), with strong nonlinear and synergistic effects. These findings validate the use of response surface analysis to optimize extrusion parameters and predict product stability. The incorporation of lentil flour, flaxseed, pumpkin powder, and semolina contributed to improved nutritional quality and functional performance, aligning with global trends in hybrid meat–plant product development. The hybrid matrix demonstrated favorable structural behavior under high-intensity extrusion, supporting the creation of shelf-stable, high-protein snacks with desirable textural attributes. Overall, this study provides new insight into the mechanisms governing water reduction, matrix formation, and rheological strengthening in meat–plant extruded systems. The identified processing conditions offer a robust technological framework for industrial-scale production of hybrid extruded products with improved quality, stability, and nutritional value.

REFERENCES

1. Dekkers, B. L., Boom, R. M., & van der Goot, A. J. (2018). Structuring processes for meat analogues. *Trends in Food Science & Technology*, 81, 25–36. <https://doi.org/10.1016/j.tifs.2018.08.011>
2. Chen, X., Xu, X., Liu, D., Zhou, G., Han, M., & Wang, P. (2018). Rheological behavior, conformational changes and interactions of water-soluble myofibrillar protein during heating. *Food Hydrocolloids*, 77, 524–533. <https://doi.org/10.1016/j.foodhyd.2017.10.030>
3. Palanisamy, M., Töpfl, S., Berger, R. G., & Hertel, C. (2019). Physico-chemical and nutritional properties of meat analogues based on Spirulina/lupin protein mixtures. *European Food Research and Technology*, 245(9), 1889–1898. <https://doi.org/10.1007/s00217-019-03298-w>
4. Osen, R., Toelstede, S., Wild, F., Eisner, P., & Schweiggert-Weisz, U. (2014). High moisture extrusion cooking of pea protein isolates: Raw material characteristics, extruder responses, and texture properties. *Journal of Food Engineering*, 127, 67–74. <https://doi.org/10.1016/j.jfoodeng.2013.11.023>
5. Bohrer, B. M. (2017). Review: Nutrient density and nutritional value of meat products and non-meat foods high in protein. *Trends in Food Science & Technology*, 65, 103–112. <https://doi.org/10.1016/j.tifs.2017.04.016>
6. Kyriakopoulou, K., Dekkers, B., & van der Goot, A. J. (2019). Plant-Based Meat Analogues. In *Sustainable Meat Production and Processing* (pp. 103–126). Elsevier. <https://doi.org/10.1016/b978-0-12-814874-7.00006-7>
7. Zhang, J., Liu, L., Jiang, Y., Shah, F., Xu, Y., & Wang, Q. (2020). High-moisture extrusion of peanut protein-/carrageenan/sodium alginate/wheat starch mixtures: Effect of different exogenous polysaccharides on the process forming a fibrous structure. *Food Hydrocolloids*, 99, 105311. <https://doi.org/10.1016/j.foodhyd.2019.105311>
8. Riaz, M. N. (2011). Texturized vegetable proteins. In *Handbook of Food Proteins* (pp. 395–418). Elsevier. <https://doi.org/10.1533/9780857093639.395>
9. Schmid, E., Farahnaky, A., Adhikari, B., & Torley, P. J. (2022). High moisture extrusion cooking of meat analogs: A review of mechanisms of protein texturization. *Comprehensive Reviews in Food Science and Food Safety*, 21(6), 4573–4609. <https://doi.org/10.1111/1541-4337.13030>
10. Dekkers, B. L., Nikiforidis, C. V., & van der Goot, A. J. (2016). Shear-induced fibrous structure formation from a pectin/SPI blend. *Innovative Food Science & Emerging Technologies*, 36, 193–200. <https://doi.org/10.1016/j.ifset.2016.07.003>
11. Toldrá, F., Aristoy, M.-C., Mora, L., & Reig, M. (2012). Innovations in value-addition of edible meat by-products. *Meat Science*, 92(3), 290–296. <https://doi.org/10.1016/j.meatsci.2012.04.004>
12. Zhang, W., Xiao, S., Samaraweera, H., Lee, E. J., & Ahn, D. U. (2010). Improving functional value of meat products. *Meat Science*, 86(1), 15–31. <https://doi.org/10.1016/j.meatsci.2010.04.018>
13. Lin, S., Huff, H. E., & Hsieh, F. (2002). Extrusion Process Parameters, Sensory Characteristics, and Structural Properties of a High Moisture Soy Protein Meat Analog. *Journal of Food Science*, 67(3), 1066–1072. <https://doi.org/10.1111/j.1365-2621.2002.tb09454.x>
14. Mironeasa, S., Coțovanu, I., Mironeasa, C., & Ungureanu-Iuga, M. (2023). A Review of the Changes Produced by Extrusion Cooking on the Bioactive Compounds from Vegetal Sources. *Antioxidants*, 12(7), 1453. <https://doi.org/10.3390/antiox12071453>
15. Zhang, J., Chen, Q., Kaplan, D. L., & Wang, Q. (2022). High-moisture extruded protein fiber formation toward plant-based meat substitutes applications: Science, technology, and prospect. *Trends in Food Science & Technology*, 128, 202–216. <https://doi.org/10.1016/j.tifs.2022.08.008>
16. Samard, S., & Ryu, G. H. (2019). Physicochemical and functional properties of plant protein-based meat analogs. *Journal of Food Processing and Preservation*, 43(10), e14123. <https://doi.org/10.1111/jfpp.14123>
17. Wittek, P., Zeiler, N., Karbstein, H. P., & Emin, M. A. (2021). High Moisture Extrusion of Soy Protein: Investigations on the Formation of Anisotropic Product Structure. *Foods*, 10(1), 102. <https://doi.org/10.3390/foods10010102>
18. Wang, Y., Wang, Y., Li, K., Bai, Y., Li, B., & Xu, W. (2020). Effect of high intensity ultrasound on physicochemical, interfacial and gel properties of chickpea protein isolate. *LWT*, 129, 109563. <https://doi.org/10.1016/j.lwt.2020.109563>
19. Yang, Z., Swedlund, P., Gu, Q., Hemar, Y., & Chaieb, S. (2016). Retrogradation of Maize Starch after High Hydrostatic Pressure Gelation: Effect of Amylose Content and Depressurization Rate. *PLOS ONE*, 11(5), e0156061. <https://doi.org/10.1371/journal.pone.0156061>

20. Chen, F. L., Wei, Y. M., & Zhang, B. (2011). Chemical cross-linking and molecular aggregation of soybean protein during extrusion cooking at low and high moisture content. *LWT - Food Science and Technology*, 44(4), 957–962. <https://doi.org/10.1016/j.lwt.2010.12.008>
21. Zhong, Y., Bertoft, E., Li, Z., Blennow, A., & Liu, X. (2020). Amylopectin starch granule lamellar structure as deduced from unit chain length data. *Food Hydrocolloids*, 108, 106053. <https://doi.org/10.1016/j.foodhyd.2020.106053>

Funds:

This work was supported by the scientific and technical program for 2024-2026 “Development of technologies for integrated and deep processing of agricultural raw materials for food production ensuring high quality and safety of manufactured products” (Program code BR24892775), funded by the Ministry of Agriculture of the Republic of Kazakhstan. The research was carried out within the framework of the project “Development of a technology for the production of combined meat products based on animal and plant raw materials with extended shelf life using extrusion technology.”

Acknowledgments:

-

Competing Interests:

No potential conflict of interest was reported by the author(s).

Ethical Statement:

This article does not contain any studies that would require an ethical statement.

AI Statement:

AI tools (e.g., ChatGPT, GPT-5-mini) were used to assist with manuscript preparation, including text editing, rephrasing, and improving clarity of the discussion and limitations sections. All scientific content, data analysis, and interpretation were conducted by the authors.

Contact Address:

Nurzhan Tultabayev

Kazakh Scientific Research Institute of Processing and Food Industry, Department of Food Technology, 238 Gagarin Avenue, Almaty 050060, Kazakhstan,

Tel.: +7 778 588 66 00

E-mail: tultabaevn@bk.ru

ORCID: <https://orcid.org/0000-0002-3178-8991>

Author contribution: writing – original draft, data curation, formal analysis.

Urishbay Chomanov

Kazakh Scientific Research Institute of Processing and Food Industry, Department of Food Technology, 238 Gagarin Avenue, Almaty 050060, Kazakhstan,

Tel.: +7 701 788 4556

E-mail: chomanov_u@mail.ru

ORCID: <https://orcid.org/0000-0002-5594-8216>

Author contribution: investigation, data curation, formal analysis, validation.

Gulmira Kenenbay

Kazakh Scientific Research Institute of Processing and Food Industry, Department of Food Technology, 238 Gagarin Avenue, Almaty 050060, Kazakhstan,

Tel.: +7 702 320 5856

E-mail: gkenenbay@mail.ru

ORCID: <https://orcid.org/0000-0002-8332-8102>

Author contribution: conceptualisation, methodology, supervision, writing – review & editing, project administration.

Torgyn Zhumaliyeva

Kazakh Scientific Research Institute of Processing and Food Industry, Department of Food Technology, 238 Gagarin Avenue, Almaty 050060, Kazakhstan,

Tel.: +7 777 127 4729

E-mail: torgynzh@gmail.com

ORCID: <https://orcid.org/0000-0002-1175-935X>

Author contribution: writing – editing, visualization.

Corresponding author: **Nurzhan Tultabayev**

Copyright notice:

© 2026 The Author(s). Published by HACCP Consulting, Slovakia, European Union, on *Scifood* (<https://scifood.eu>), the official website of the journal. *Scifood* is owned and operated by HACCP Consulting s.r.o. (<https://www.haccp.sk>). This article is published as **Open Access** under the **Creative Commons Attribution–NonCommercial–NoDerivatives 4.0 International License** <https://creativecommons.org/licenses/by-nc-nd/4.0/> (CC BY-NC-ND 4.0). This license permits non-commercial use, sharing, distribution, and reproduction in any medium or format, provided that appropriate credit is given to the author(s) and the original publication, a link to the license is provided, and the work is not modified, adapted, or transformed.