

Impact of Extruded Pea Hull Fibres and Starch on Texture and Sensory Properties of Meat Analogues

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Abstract. Pea hulls, a by-product of pea protein production, represent a valuable source of dietary fibre, and its utilisation supports the implementation of zero-waste approaches in the development of new products. The incorporation of pea starch and extruded pea hulls as fibre sources in high-moisture extruded meat analogues represents a promising approach to obtaining products with desirable textural properties while increasing dietary fibre content. In contrast, the incorporation of fibre may disrupt the homogeneous protein–starch matrix, resulting in a less fibrous structure with shorter fibres. The aim of this study was to investigate the effect of extruded pea hull fibre and starch on structure formation, texture, colour, and sensory properties of high-moisture extrudates formulated with pea protein and pea starch. The formulations were based on 80% pea protein isolate (P) and 20% pea starch (S), with extruded pea hulls (F) added at levels of 5%, 10%, and 15% by partially replacing starch. High-moisture extrusion was performed using a twin-screw extruder. Texture profile analysis showed that, compared with extruded pea protein isolate, the hardness and chewiness of samples containing starch and extruded fibre were increase. Similar trends were observed during sensory evaluation, where experts noted that the addition of extruded pea hulls reduced perceived fibrousness, resulting in softer samples that were easier to chew and more closely resembled meat texture. Moderate replacement of starch with extruded pea hulls (10%) in high-moisture extruded products may improve textural properties and provide a basis for further research into meat analogue development.

Key words: high-moisture extrusion, meat analogue, pea protein, pea hulls, dietary fibre.

Introduction

The production and processing of plant-based products is steadily increasing (Sha & Xiong, 2020; Theng *et al.*, 2025), driven by sustainability goals and the growing popularity of vegetarian diets (Tachie *et al.*, 2023). Consequently, plant-derived raw materials are increasingly used in the development of meat alternatives. Legume proteins, such as lentils, beans, and peas, are widely used in the production of meat analogues (Bohrer, 2019). Pea processing yields multiple fractions – protein, starch, and pea hull fibre. The latter is considered a by-product rich in insoluble

dietary fibre (Rasul *et al.*, 2025). All fractions possess functional properties that enable their use in the development of plant-based meat analogues (Bohrer, 2019; Plattner *et al.*, 2024).

High-moisture (>40%) extrusion is widely used for protein fibrillation to produce fibrous meat analogues (X. Zhang *et al.*, 2024). Extrusion parameters and raw material composition significantly influence textural and sensory properties of the final product (Kaleda *et al.*, 2021; Ramos Diaz *et al.*, 2022). By adjusting the proportions of protein, starch, and dietary fibre, diverse physical properties are achieved by altering

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biopolymer interactions and morphology during extrusion (Jebalia *et al.*, 2019).

Protein serves as the primary structural basis in plant-based meat analogues (Gasparre *et al.*, 2022). The development of meat-like fibrous or anisotropic structures is fundamentally driven by the unfolding, aggregation, and cross-linking of protein molecules. Phase separation may also occur within the same protein system due to differences in protein fractions and/or conformations (Witteck *et al.*, 2021). However, commercial meat analogues commonly employ two polymers, typically a protein combined with another protein or a carbohydrate, as at least two distinct phases are required to generate an anisotropic structure (Van der Sman & Van der Goot, 2023). Protein and its interactions with other ingredients therefore play a crucial role in shaping the sensory perception of meat analogues, particularly by contributing to a meat-like texture (Schmid *et al.*, 2022). Pea proteins are increasingly important components in the formulation of meat analogues, complementing the traditionally dominant use of soy and wheat proteins.

Starch is incorporated as a structuring agent or filler, enhancing intermolecular interactions between protein and other constituents and forming a stable structure through gelatinisation (Bohrer, 2019). The rheological, water-absorption, and thermal properties of starch are largely determined by its amylose and amylopectin fractions, which significantly influence the structural development of extrudates. Amylopectin is known to promote the formation of fibrous structures by facilitating protein rearrangement, aggregation, and cross-linking during extrusion, thereby contributing to more uniform and elastic fibres. Consequently, the amylose–amylopectin ratio is considered an important factor in determining the final structural and textural properties of extruded products (Chen *et al.*, 2022). Starches of different botanical origins exhibit distinct amylose–amylopectin ratios. Potato starch typically contains approximately 15–30% amylose, whereas pea starch generally contains around 30–40%, which can lead to different functional behaviours during processing (Ahmad *et al.*, 2025; Mir *et al.*, 2019; Ratnayake *et al.*, 2001; Ubaid *et al.*, 2026; S. Zhang *et al.*, 2025). Due to its hypoallergenic characteristics and cost advantages compared with some conventional starch sources, pea starch has attracted increasing interest as an industrial ingredient (Johansson *et al.*, 2026; Ratnayake *et al.*, 2001).

Research indicates that the inclusion of dietary fibre can improve extrudate quality, particularly in terms of water absorption and structure formation. The functional role of dietary fibre depends on its chemical composition, especially the ratio of soluble to insoluble fractions, as well as particle characteristics,

such as size and morphology (Gutöhrlein *et al.*, 2020). Insoluble dietary fibres are commonly extracted from plant-based materials, including legumes and vegetable processing by-products (Marczak & Mendes, 2024; Rasul *et al.*, 2025). Pea hull fibre represents a particularly rich source of insoluble dietary fibre, typically accounting for approximately 71–92 g 100 g⁻¹ of the material. It also contains smaller amounts of starch (1–12 g 100 g⁻¹), soluble fibre, and minor quantities of protein (4–14 g 100 g⁻¹) (Johansson *et al.*, 2026; Ramirez *et al.*, 2021). The major structural components of pea hulls include cellulose, hemicellulose, and pectin, with pectin contributing significantly to water-binding capacity. Cellulose consists of linear chains of glucopyranose units linked by β -(1→4) glycosidic bonds. Hydrogen bonding between cellulose fibres and proteins may promote protein-insoluble dietary fibre interactions, which can contribute to increased hardness and structural stability in gel-like meat analogue matrices (Cheng *et al.*, 2024; Rasul *et al.*, 2025).

Different dietary fibre fractions can be incorporated into extrudate formulations, including soluble fractions capable of forming gels and fractions rich in insoluble fibre (Bohrer, 2019). Soluble fibres, which often function as hydrocolloids, exhibit strong water-binding and gel-forming properties (Rasul *et al.*, 2025). Insoluble fibres, such as cellulose, tend to increase the firmness of meat analogues and may contribute to macroscopic phase separation within the protein matrix. In contrast, soluble fibres, such as pectin, generally soften the structure while enhancing water-binding capacity (Van der Sman & Van der Goot, 2023). Insoluble fibres can therefore serve as functional ingredients that improve structural properties and promote the formation of stable textures in meat analogues (Theng *et al.*, 2025). The incorporation of moderate amounts of dietary fibre enables the targeted adjustment of textural properties, which may enhance the overall appearance and nutritional value of meat analogue products (Wagner & Ganjyal, 2024). The resulting textural characteristics depend largely on the water-binding capacity of the ingredients, which influences moisture distribution and contributes to the development of the desired fibrous structure in the final product.

However, extruded pea hull fibres may behave differently from conventional dietary fibres due to structural and compositional modifications induced during the extrusion process (Klava *et al.*, 2024). Extrusion can partially disrupt the fibre matrix, increasing the proportion of soluble fractions and altering physicochemical properties such as water-binding capacity and swelling behaviour. As a result, extruded pea hull fibres may influence moisture

distribution, structural organisation, and texture development in plant-based meat analogues differently from native fibres. Despite increasing interest in fibre-enriched meat analogues, the functional role of extruded pea hull fibre in high-moisture extrusion systems remains insufficiently understood. In particular, limited information is available on how these modified fibres interact with pea protein and alternative starch sources during structure formation and how they affect the physical and sensory properties of the final product.

Therefore, the aim of this study was to investigate the effect of extruded pea hull fibre and starch on structure formation, texture, colour, and sensory properties of high-moisture extrudates formulated with pea protein and pea starch.

Materials and Methods

Ingredients used in blend preparation and their characteristics

Commercial pea (*Pisum sativum* L.) protein isolate powder (light yellow colour, neutral flavour) was obtained from Exeller Polska Sp.z o.o (Piaseczno, Poland). The manufacturer-reported composition was: protein 74.0%, fibres 4.0%, fat 8.0%, ash 6.0%, and moisture 8%.

Commercial pea (*Pisum sativum* L.) starch (white colour, neutral taste) was obtained from Cosucra Groupe Warcoing S.S (Warcoing, Belgium). The characteristics of the pea starch isolate were as follows: total carbohydrates 99% on a dry matter (DM) basis, dietary fibres 0.2%, proteins 0.15% and ash 0.2%.

Commercial potato starch (white powder, neutral taste) was obtained from LTD "Aloja Starkelsen" (Aloja, Latvia). Potato starch contained total carbohydrates 99%, dietary fibres 0.4%, proteins 0.2%, and ash 0.2%.

Pea hulls (ASNS Ingredient, Jelgava, Latvia) derived from yellow peas (*Pisum sativum* L.) were used. Their physico-chemical properties were as

follows: dry matter content of 91%, fibre at 51% (DM), proteins 6.0% (DM), starch 27% (DM), and ash 7% (DM). Before extrusion experiments, the extruded pea hulls were milled with in Retsch SM 100 cutting mill (Retsch GmbH, Haan, Germany) fitted with a 1 mm sieve. The material was then further milled for 10 minutes 437 rpm in a Retsch PM 100 planetary ball mill equipped with a 500 mL vessel and six steel balls (3 cm diameter), with the direction reversed every 3 minutes. The final volume-weighted particle size distribution was D10 = 19.3 µm, D50 = 99.7 µm, and D90 = 258.6 µm.

Composition of blends

Powder blends were prepared following the recipes in Table 1. The ingredients were mixed for 10 minutes using Spicer 50 mixer (Ekeby Rostfria Produktions AB, Bjur, Sweden).

Meat analogue extrusion

A total of six batches, each 10 kg were prepared and processed by extrusion. Powder (moisture content 6–9%) were processed using a co-rotating, intermeshing twin-screw extruder, KETSE 20/40 (Brabender GmbH, Duisburg, Germany), with a long cooling die (2 × 7 × 700 mm, W × H × L). The mass flow rate was set constant by calibrating the volumetric feeder with each powder. Water was added through a separate port using a calibrated peristaltic pump. The actual mass flow rate was measured by collecting the extrudate for 1 min. Suitable extrusion conditions were determined in a preliminary trial. The temperature profile was set to 40, 80, 137, and 155 °C. The screw rotation speed was set to 1000 rpm. The cooling die temperature was maintained at 55 °C with a tempering unit, but only in the last 300 mm, thus creating a temperature gradient along the die to enhance fibre formation. Moisture content was adjusted for each blend, and samples were collected when the process reached stability, as evidenced by measured pressure, temperature, and motor load. The samples were packed into zip-lock bags and frozen at –40 °C, then stored at –18 °C

Table 1

Sample code and composition

Raw material sample code	Composition of powder blends	Extruded product sample code
P	100% pea protein isolate	EP
P-PS	80% pea protein isolate, 20% potato starch	EP-PS
P-S	80% pea protein isolate, 20% pea starch	EP-S
P-S-F5	80% pea protein isolate, 15% pea starch, 5% pea hulls	EP-S-F5
P-S-F10	80% pea protein isolate, 10% pea starch, 10% pea hulls	EP-S-F10
P-S-F15	80% pea protein isolate, 5% pea starch, 15% pea hulls	EP-S-F15

until analysis. Before evaluation, the samples were thawed under refrigerated conditions for 12 h and then rehydrated by soaking in water at room temperature (22–23 °C) for 10 min.

Physicochemical analysis

Moisture content was measured using a halogen moisture analyser (HX204, Mettler Toledo, Germany) in three replicates.

Total dietary fibre (TDF) was measured by the enzymatic-gravimetric method, following AOAC 985.29 (AOAC 985.29, 2023). The determination was carried out using a Megazyme total dietary fibre kit (Wicklow, Ireland).

Protein was analysed by the Kjeldahl method with a Kjeltec system 2100 in combination with a Tecator™ Digester and Distilling unit (FOSS, Höganäs, Sweden). The protein content was calculated using a nitrogen-to-protein conversion factor of 6.25.

Starch was tested in accordance with ISO 10520:1997 (ISO, 2024).

Chemical composition measurements were performed in duplicate and was reported on a dry matter (DM) basis.

For pH determination of blends and lyophilised extrudates, a suspension was prepared by mixing 5 g of powder with 25 g of distilled water. The pH value was measured using a pH meter SevenCompact™ S220 (Mettler Toledo, Switzerland) in triplicate.

Water holding capacity (WHC) and oil holding capacity (OHC) were measured as described by researcher Kaleda (Kaleda et al., 2021). The sample, consisting of 1 g of the blend, was dispersed in 10 mL of distilled water or rapeseed oil, and the mixture was gently mixed by hand for 30 minutes. The suspension was subsequently centrifuged at 3000 × g for 15 min. The water and oil supernatants were carefully decanted, and the residual liquid was weighed. WHC and OHC were expressed as grams of water or oil retained per gram of blend (g/g). The samples were analysed in three replicates.

For physicochemical analyses, the extrudates were lyophilised in a freeze-dryer FrostX10 (FrostX Sp. z o.o., Gliwice, Poland) at 120 Pa for 24 h and subsequently ground using a laboratory mill (Foss Knifetec 295 Mill, Foss Analytical Co., Ltd, Sizou, China). Until analysis, the samples were stored in plastic bags.

Colour

A ColorFlex instrument (Hunter LAB, Reston, VA, USA) based on the CIE L*a*b* colour system was used. Colour parameters (L*, a*, b*) were measured using a ColorFlex spectrophotometer (Hunter LAB, Reston, VA, USA) based on the CIE L*a*b* system. The total colour difference (ΔE) was calculated using Formula (1):

$$\Delta E = \sqrt{[(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2]}, \quad (1)$$

where: L_1^* – colour intensity (dark-light) of samples with starch and fibres;

L_2^* – colour intensity (dark-to-light) of sample EP;

a_1^* – green-to-red colour component of the samples with starch and fibres;

a_2^* – green-to-red colour component of the sample EP;

b_1^* – blue-to-yellow colour component of samples with starch and fibres;

b_2^* – blue-to-yellow colour component of the sample EP (Kirse-Ozolins et al., 2019).

Texture profile analysis

Texture profile analysis (TPA) of the extrudates was performed using a texture analyser TA.HD.Plus (Stable Microsystems, Godalming, UK), equipped with a 30 kg load cell. Test samples were prepared with dimensions of 20 × 20 × 5 mm. Each sample was compressed to 50% of its thickness using a 25 mm cylindrical aluminium probe at a constant speed of 1 mm s⁻¹. A 5-second interval was applied between compression cycles to allow decompression. Hardness (maximum force during the first compression peak), adhesiveness, springiness, cohesiveness, and chewiness were calculated. The samples were analysed after 12 hours of storage at 4 °C in the refrigerator following removal from the freezer. The anisotropy index was determined as the ratio of the perpendicular to parallel cutting forces, following Kantanen et al. (Kantanen et al., 2022). For each sample, parallel and perpendicular cuts of fibrous structure were performed, with eight repetitions conducted in each direction. Cutting force measurements were obtained using a knife blade (HDP/WBB, 70 mm). The instrument was set to the following parameters: test speed 2 mm s⁻¹, cutting distance 10 mm, trigger force 0.49 N.

Microstructural analysis

Samples were prepared to enable observation of both perpendicular and parallel internal structures relative to the extrusion flow. For the perpendicular cross-section, the samples were cut using a sharp blade to obtain a clean cross-section of the material. For the parallel cross-section, the samples were mechanically torn apart to expose the internal structure in the parallel direction. The prepared specimens were mounted on semi-conductive pin stubs using carbon double-sided adhesive tape to ensure proper electrical contact and stability during imaging. Prior to microscopy, the samples were coated with a thin conductive layer using a Leica EM ACE600 sputter coater (Leica Microsystems, Wien, Austria). A gold (Au) coating with a thickness of approximately 4

nm was deposited on the sample surface to prevent charging during electron microscopy analysis. Surface morphology and internal structures were examined using a TESCAN MIRA3 XMU scanning electron microscope (SEM) (Tescan Orsay Holding, a.s., Brno-Kohoutovice, Czech Republic). Imaging was performed at an accelerating voltage of 5 kV. Micrographs were acquired at magnifications of 150×. Both secondary electron (SE) and backscattered electron (BSE) detectors were used to obtain morphological and compositional contrast.

Sensory evaluation

The sensory panel, consisting of eight experts, was recruited from the staff of the Latvia University of Life Sciences and Technologies and ASNS Ingredient Ltd, who had previously worked with this type of product. Before the evaluation, a 2-hour training session was held to ensure that the experts had a common understanding of the characteristics to be evaluated and the evaluation technique.

Since the samples had been frozen previously, they were thawed in the refrigerator for 12 hours before evaluation. Before evaluation, the samples were immersed in water at room temperature (22–23 °C) and left for 10 minutes. Each expert received all samples measuring 2 × 10 cm. Each expert evaluated the intensity of the sensory attributes (hardness, elasticity, fibrousness, gummy structure, colour intensity, aroma of legumes, taste of legumes, and bitter taste) of six samples using a 9-point line scale with anchors: 1 (not at all or not pronounced) and 9 (very pronounced). The hardness of the samples was determined using a fork, assessing how easy the samples could be broken (1–3 – very easy, 7–9 – very hard, impossible to break). The elasticity of the products was determined by bending them and observing how easily they yielded during the process (1–3 – bends easily and

returns to its original shape, 7–9 – the sample breaks, not elastic). Fibrousness was analysed by trying to break the product into separate fibres (1–3 the sample breaks easily into fibres, 7–9 – impossible to obtain fibres).

The samples were presented to the experts, coded and in a randomised order. Water was used to cleanse the plate between samples.

All experts provided signed informed consent before participation. The sensory study received approval from the Ethics Committee of the Food Institute, Latvia University of Life Sciences and Technologies.

Statistical analysis

Statistically significant differences between the samples ($p < 0.05$) were evaluated through pairwise comparisons using Tukey's honestly significant difference (HSD) test. Mean values and standard deviations were calculated for all measured parameters. Principal component analysis (PCA) was applied to identify relationships among the chemical and physical characteristics of the extrudates. Pearson's correlation analysis was performed to assess the relationships between the physical and sensory properties of the extrudates. All statistical analyses were performed using the open-source software Python 3.10.12. The analysis was carried out using the libraries pandas, NumPy, Matplotlib, Statsmodels, and scikit-learn.

Results and discussion

Extrusion

The properties of raw materials determine the extrusion process parameters and the characteristics of the resulting extrudate. The conditions for production runs and recorded process parameters are outlined in Table 2. The moisture content for each recipe was adjusted during extrusion to maintain texturisation,

Table 2

Process parameters recorded during extrusion

Sample code	Feed rate, kg h ⁻¹	Moisture, %	Temperature, °C	Pressure, bar
EP	5.4±0.1 ^b	58.7±0.8 ^a	135.8±0.1 ^d	4.9±0.5 ^c
EP-PS	5.3±0.1 ^{bc}	51.4±0.6 ^c	139.5±0.2 ^c	9.2±0.6 ^a
EP-S	5.3±0.0 ^{bc}	49.5±0.6 ^d	143.4±0.4 ^{ab}	9.5±0.9 ^a
EP-S-F5	5.2±0.0 ^c	51.5±1.0 ^c	143.5±0.1 ^a	8.7±0.5 ^b
EP-S-F10	5.3±0.0 ^b	53.4±0.3 ^b	143.2±1.1 ^b	7.6±0.5 ^c
EP-S-F15	5.6±0.0 ^a	53.5±0.4 ^b	143.1±0.2 ^b	7.2±0.3 ^d

EP – extruded pea protein isolate; EP-PS – extruded 80% pea protein isolate, 20% potato starch; EP-S – extruded 80% pea protein isolate, 20% pea starch; EP-S-F5 – 80% pea protein isolate, 15% pea starch, 5% pea hulls; EP-S-F10 – 80% pea protein isolate, 10% pea starch, 10% pea hulls; EP-S-F15 – 80% pea protein isolate, 5% pea starch, 15% pea hulls. Values within a column not sharing a letter are statistically significantly different ($p < 0.05$).

Table 3

Physicochemical properties of powder blends.

Sample code	pH	WHC (g H ₂ O g ⁻¹)	OHC (g H ₂ O g ⁻¹)
P	6.32±0.01 ^{cd}	2.14±0.05 ^a	2.70±0.01 ^a
P-PS	6.38±0.01 ^a	2.06±0.07 ^a	2.24±0.25 ^c
P-S	6.37±0.01 ^{ab}	2.12±0.06 ^a	2.42±0.01 ^{bc}
P-S-F5	6.35±0.02 ^{bc}	2.15±0.02 ^a	2.64±0.02 ^a
P-S-F10	6.30±0.01 ^{de}	2.00±0.13 ^a	2.54±0.05 ^{ab}
P-S-F15	6.28±0.01 ^e	2.18±0.08 ^a	2.30±0.03 ^c

WHC – water holding capacity, OHC – oil holding capacity. Values within a column not sharing a letter are statistically significantly different ($p < 0.05$).

and it ranged from 49.5% to 58.7%. The highest feed moisture was observed during the extrusion of sample EP, which can be attributed to the high solubility of pea proteins. When 20% of starch was added to the protein isolate during extrusion, the moisture content decreased by approximately 6% on average. When comparing samples containing potato starch and pea starch, a higher feed moisture was required during EP-PS extrusion (51.4%). This can be explained by the composition of potato starch, which contains a higher proportion of amylopectin, thereby increasing water-binding capacity (Horstmann *et al.*, 2016). The addition of 10% and 15% extruded pea fibre to the samples increased the water-binding capacity compared with the EP-S and EP-PS samples; however, it did not reach the moisture level of the protein isolate sample. Scientific studies on the water-binding capacity of dietary fibre in bread production indicate that water binding increases with longer dough preparation time, and in samples containing 15% fibre, it can reach up to 25 minutes (Klava *et al.*, 2024). In contrast, the high-moisture extrusion process usually lasts no more than 10 minutes.

Water holding capacity (WHC) and oil holding capacity (OHC) are important functional properties in the development of meat analogues, as they significantly influence product texture, juiciness, and overall sensory quality. No significant differences in water holding capacity between powder blends were observed, except that of the sample P-S-F15 was slightly higher than the others (Table 3). Water absorption is influenced by the type of protein used; for example, soy protein has been reported to exhibit higher water holding capacity compared with pea protein isolate and oat protein isolate (de Angelis *et al.*, 2020). Previous observations by other authors have shown a higher WHC of 2.82 and 2.51 g H₂O g⁻¹ for pea isolate, but lower OHC of 1.11 and 0.91 g H₂O g⁻¹ (de Angelis *et al.*, 2020; Kaleda *et al.*, 2021).

The inclusion of starch and fibre reduced the OHC in comparison to pure protein isolate. The physicochemical properties of pea protein ingredients are known to be influenced by protein isolate purity, processing treatments, and cultivar differences (Foley *et al.*, 2025).

Starch swelling and gelatinisation properties exerted the strongest influence on extrusion pressure. In contrast, pea hull dietary fibre showed a significantly lower pressure when combined with starch, but a higher pressure compared with pure protein isolate, likely due to the ability of pea hull fibre to increase mixture viscosity during extrusion (Wagner & Ganjyal, 2024).

Microstructure analysis

The addition of starch to high-moisture extrusion significantly influences the structural formation of plant-based meat analogues. The functional role of starch in the protein-starch matrix depends on several physicochemical properties, including its botanical origin, amylose content, granule size, and swelling capacity. Potato and pea starches exhibit different structural behaviours during extrusion, which allow targeted modulation of the final product's texture, juiciness, and mechanical stability. In addition to starch, insoluble dietary fibre can further affect structure formation. The incorporation of dietary fibre may increase structural firmness through the development of stronger interactions within the protein-starch-fibre matrix. Hydrogen bonding between fibres and proteins contributes to increased hardness and rigidity in the gel-like structures of meat analogues (Chiang *et al.*, 2019). From a technological perspective, the selection of starch type should be guided by the desired product characteristics. Potato starch tends to promote a juicier and more elastic texture, whereas pea starch may enhance fibrousness and mechanical stability in the final product.

The microstructure of the extruded samples highlighted clear differences in fibre formation as a

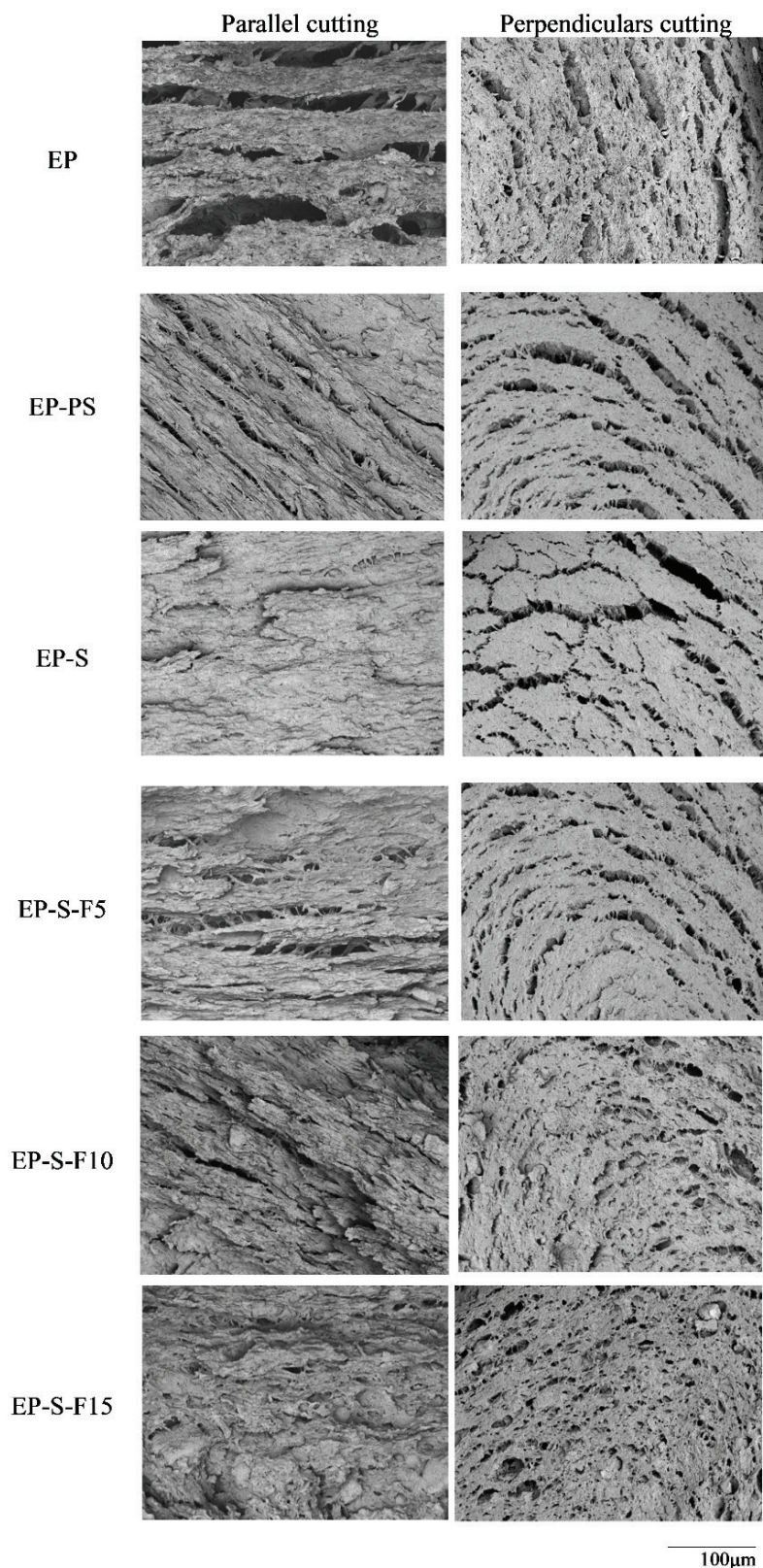


Figure 1. Microstructure of extruded products.

EP – extruded pea protein isolate; EP-PS – extruded 80% pea protein isolate, 20% potato starch; EP-S – extruded 80% pea protein isolate, 20% pea starch; EP-S-F5 – 80% pea protein isolate, 15% pea starch, 5% pea hulls; P-S-F10 – 80% pea protein isolate, 10% pea starch, 10% pea hulls; EP-S-F15 – 80% pea protein isolate, 5% pea starch, 15% pea hulls.

function of starch type and the addition of extruded pea fibre (Figure 1). The reference sample containing only pea protein (EP) exhibited a coarse and relatively compact structure with irregular void spaces and limited fibre alignment. Although some elongated cavities (delaminated layers) were visible in the parallel cutting direction, the overall morphology remained dense and poorly organised, indicating limited phase separation during extrusion. The addition of potato starch (EP-PS) substantially enhanced fibre formation. In the parallel cutting direction, well-aligned layered structures were observed, indicating strong anisotropy and effective structuring during high-moisture extrusion.

In the perpendicular direction, the structure exhibited pronounced lamellar patterns, confirming the formation of oriented protein domains. This behaviour can be attributed to the high swelling capacity and lower amylose content of potato starch, which promotes water redistribution and facilitates protein alignment during the cooling phase of extrusion. Potato starch generally has a lower amylose content than pulse starches, while starch swelling and the amylose/amylopectin balance are known to affect viscosity, gelation, and final structure formation (Jia *et al.*, 2023). In contrast, samples containing pea starch (EP-S) showed a less pronounced fibrous morphology. The structure appeared more compact and gel-like, with shorter and less distinct fibres. This interpretation is consistent with the generally higher amylose content reported for pea starch compared with potato starch. Higher amylose content are associated with stronger gelling tendencies and can alter water partitioning, microstructure, and mechanical behaviour in starch-protein systems (Wu *et al.*, 2023). The incorporation of extruded pea fibre further modified the microstructure. In the EP-S-F5 formulation, the structure became more layered and fibrous compared

with the sample containing only pea starch. The fibres appeared shorter but more clearly defined, and the matrix exhibited a more uniform and finely porous morphology. Similar trends have been reported for insoluble dietary fibre addition in pea-protein-based high-moisture extrudates, where moderate fibre incorporation promoted anisotropy and modified water binding and matrix organisation (Theng *et al.*, 2025). A further increase in fibre content (EP-S-F10 and EP-S-F15) resulted in a more heterogeneous and porous structure of the meat analogue products. Although some aligned structural features were still visible, the matrix appeared less continuous. This observation may be related to competition for water between fibre and protein components during extrusion. Moreover, the presence of large insoluble fibre particles can serve as physical barriers, which can interfere with protein-protein interactions and hinder the formation of a continuous protein network. Similar effects of insoluble dietary fibre on the structuring of plant-protein-based extrudates have been reported in previous studies (Klava *et al.*, 2024).

Physicochemical characteristics of extrudates

Unlike meat, whose structure is mainly determined by animal proteins, plant-based meat analogues frequently include polysaccharides such as starch and dietary fibre. These ingredients are primarily added for technological functions, including texture development and ingredient binding. Consequently, plant-based meat analogues contain carbohydrates and dietary fibre that are practically absent in meat, resulting in a product with a markedly different nutritional profile (Yang *et al.*, 2023). The protein content in the extrudate samples decreased with the addition of starch and fibre to the composition (Table 4).

The fibre content in the samples varied proportionally to the amount of added extruded pea

Table 4

Nutritional composition of extrudates, g 100g⁻¹ DM

Sample code	Protein	Fat	Starch	Ash	Total dietary fibre
EP	86.04±0.65 ^a	4.20±0.01 ^a	4.82±0.14 ^f	3.93±0.37 ^a	8.2±2.1 ^b
EP-PS	68.18±0.03 ^c	2.96±0.06 ^{bc}	22.93±0.21 ^a	2.36±0.05 ^b	6.10 ±2.4 ^b
EP-S	69.25±0.22 ^{bc}	2.42±0.05 ^d	21.47±0.09 ^b	2.99±0.06 ^b	11.11±1.5 ^a
EP-S-F5	68.67±0.05 ^{bc}	2.47±0.15 ^d	19.38±0.11 ^c	2.57±0.20 ^b	13.10±1.2 ^a
EP-S-F10	68.94±0.01 ^{bc}	2.73±0.04 ^{cd}	15.72±0.87 ^d	2.77±0.16 ^b	14.65±1.8 ^a
EP-S-H15	69.47±0.18 ^b	3.11±0.07 ^b	12.91±0.08 ^e	2.73±0.27 ^b	15.7±3.1 ^a

EP – extruded pea protein isolate; EP-PS – extruded 80% pea protein isolate, 20% potato starch; EP-S – extruded 80% pea protein isolate, 20% pea starch; EP-S-F5 – 80% pea protein isolate, 15% pea starch, 5% pea hulls; P-S-F10 – 80% pea protein isolate, 10% pea starch, 10% pea hulls; EP-S-F15 – 80% pea protein isolate, 5% pea starch, 15% pea hulls. Values within a column not sharing a letter are statistically significantly different ($p < 0.05$).

hulls. The fibre content in the samples EP-S-F10 and EP-S-F15 meets the criteria for a “high fibre” claim, which applies when a product contains at least 6 g of fibre per 100 g from Regulation (EC) No 1924/2006 of the European Parliament and of the Council of 20 December 2006 on nutrition and health claims made on foods (Regulation, 2006). Considering the moisture content of the extruded product after defrosting and soaking (Table 5), the fibre content was accordingly 6.48 g and 6.69 g per 100g of product. All samples correspond to products eligible for a “high protein” claim (29.6–33.95% of the energy value of the food).

The moisture of extrudates after defrosting and rehydration was by 3–8% higher than that measured immediately after extrusion, with the greatest increase observed in samples EP-S and EP-S-F15 (Table 5).

The pH of the extrudate was slightly lower than the pH of the powder blends, with the lowest mean value (6.29 ± 0.02) observed for the EP-S-F15. The colour changes observed in the extruded samples are related to both the composition of the raw materials and the processes induced by thermal treatment (Table 5). Pea protein isolate is naturally light in colour; however, extruded pea fibre exhibits a cream-brown tone, which contributes to colour variations in the final product. In addition, colour development during extrusion is influenced by the Maillard reaction between amino acids and reducing sugars, which intensifies brown pigmentation in the extruded samples (Jebalia *et al.*, 2019). However, the Maillard reaction may represent only one of several contributing mechanisms, as browning during extrusion can also result from caramelisation or the thermal degradation of raw material components.

Texture profile analysis

The results of the texture profile analysis (TPA) are presented in Figure 2. The hardness, springiness, cohesiveness, and chewiness of the extruded meat analogues are illustrated using box-and-whisker plots. Mean hardness values ranged from 75.56 to 145.55 N, indicating considerable variability among the samples.

The pure pea protein sample (EP) and the potato starch-containing sample (EP-PS) exhibited the highest mean hardness values, 146 N and 145 N, respectively. Among the analysed samples, EP-S showed the lowest mean hardness (76 N), indicating the softest texture. This effect may be attributed to the relatively high amylose content of pea starch, which dissolves during gelatinisation and contributes to gel formation (Jakhjoukh *et al.*, 2026; S. Zhang *et al.*, 2025). The addition of fibre resulted in a slightly harder structure compared to EP-S, but the difference was not significant ($p > 0.05$). Hardness values of fibre-containing samples did not differ substantially, ranging from 112 to 119 N.

In general, the addition of insoluble dietary fibre can increase structural rigidity due to the formation of stronger interactions within the protein–starch–fibre matrix. Hydrogen bonding between fibre and protein contributes to increased hardness in meat analogue gel structures (Cheng *et al.*, 2024; Rasul *et al.*, 2025). However, prior extrusion of the fibre may have disrupted its structure, thereby limiting the formation of strong intermolecular interactions.

Springiness measures how well the sample returns to its original height after the first compression before the second compression. The EP sample exhibited the lowest springiness, which was significantly different from that of EP-S-F15, whereas no significant differences were observed among the other samples.

Table 5

Moisture, pH, and colour properties of extrudates

Sample code	Moisture ¹ , %	pH	Colour			
			L*	a*	b*	ΔE
EP	60.50±0.23 ^a	6.39±0.01 ^{bc}	76.3±0.14 ^a	3.6±0.05 ^{ab}	25.1±0.20 ^a	—
EP-PS	54.04±0.19 ^{de}	6.44±0.03 ^{ab}	73.9±0.8 ^{ab}	3.8±0.19 ^{bc}	24.8±0.4 ^b	2.43
EP-S	53.49±0.19 ^c	6.47±0.01 ^a	75.7±0.40 ^c	3.3±0.10 ^a	22.9±0.07 ^a	2.3
EP-S-F5	54.32±0.26 ^d	6.39±0.03 ^{bc}	74.1±0.3 ^c	3.18±0.04 ^{cd}	22.55±0.10 ^b	3.41
EP-S-F10	55.76±0.17 ^c	6.36±0.03 ^c	72.5±0.17 ^d	3.43±0.06 ^{bc}	22.53±0.11 ^b	4.59
EP-S-F15	57.36±0.22 ^b	6.29±0.02 ^d	74.7±0.24 ^{bc}	2.93±0.06 ^d	20.98±0.24 ^c	4.47

¹Moisture of samples after defrosting and rehydration. Colour components of extrudates L* – lightness, a* – redness, b* – yellowness. DE – the total colour difference. EP – extruded pea protein isolate; EP-PS – extruded 80% pea protein isolate, 20% potato starch; EP-S – extruded 80% pea protein isolate, 20% pea starch; EP-S-F5 – 80% pea protein isolate, 15% pea starch, 5% pea hulls; P-S-F10 – 80% pea protein isolate, 10% pea starch, 10% pea hulls; EP-S-F15 – 80% pea protein isolate, 5% pea starch, 15% pea hulls. Values within a column not sharing a letter are statistically significantly different ($p < 0.05$).

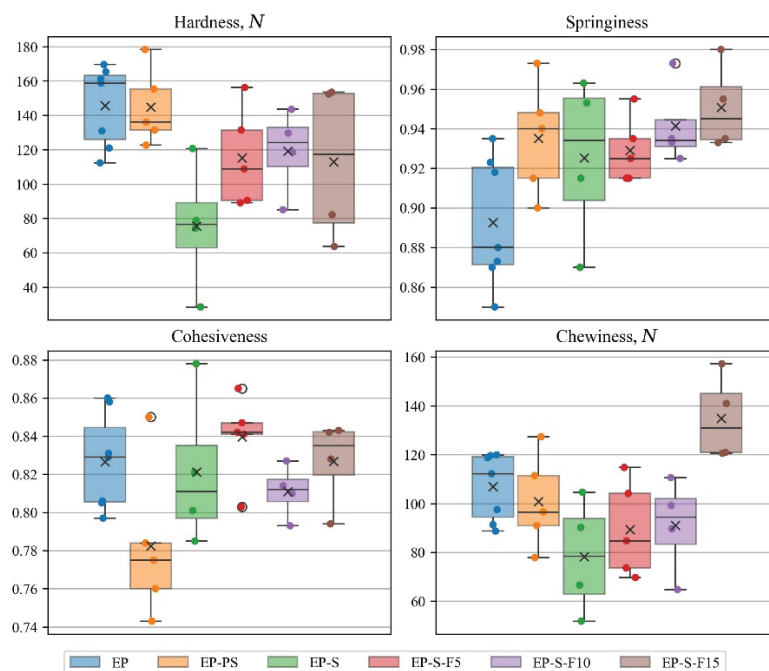


Figure 2. Texture profile analysis of extruded samples.

EP – extruded pea protein isolate; EP-PS – extruded 80% pea protein isolate, 20% potato starch; EP-S – extruded 80% pea protein isolate, 20% pea starch; EP-S-F5 – 80% pea protein isolate, 15% pea starch, 5% pea hulls; EP-S-F10 – 80% pea protein isolate, 10% pea starch, 10% pea hulls; EP-S-F15 – 80% pea protein isolate, 5% pea starch, 15% pea hulls.

During extrusion, proteins undergo denaturation and form a denser structure (Jebalia *et al.*, 2019). Starch forms a polymeric gel matrix, thereby enhancing springiness. The addition of fibre did not significantly affect the cohesiveness of the pea protein–pea starch

extrudates, meaning that the presence of fibre did not interfere with the formation of the starch gel matrix. However, the sample containing potato starch exhibited the lowest average cohesiveness, indicating a less stable structure in the protein–potato starch

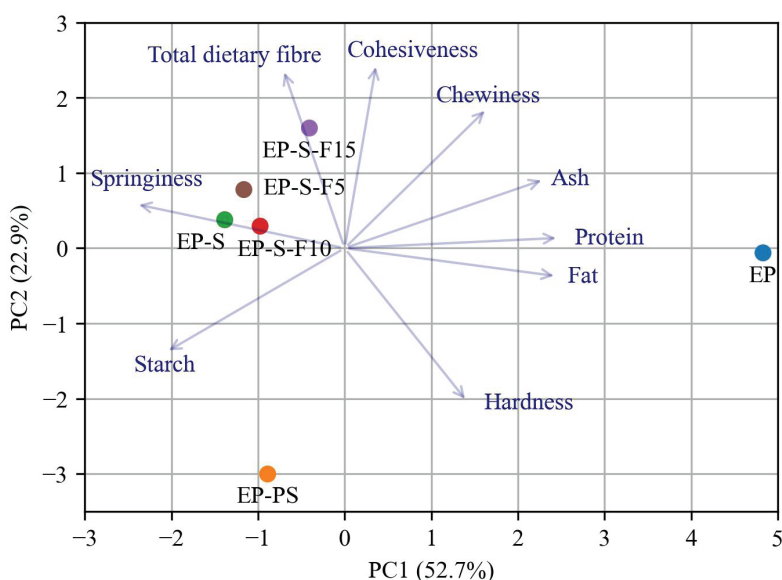


Figure 3. Principal component analysis (PCA) between chemical and physical parameters of extrudates.

EP – extruded pea protein isolate; EP-PS – extruded 80% pea protein isolate, 20% potato starch; EP-S – extruded 80% pea protein isolate, 20% pea starch; EP-S-F5 – 80% pea protein isolate, 15% pea starch, 5% pea hulls; EP-S-F10 – 80% pea protein isolate, 10% pea starch, 10% pea hulls; EP-S-F15 – 80% pea protein isolate, 5% pea starch, 15% pea hulls.

matrix. The addition of 5% and 10% fibre did not significantly affect chewiness compared with the EP-S sample; however, a 15% addition resulted in significantly higher chewiness.

Differences between the cutting forces measured perpendicular and parallel to the extrusion flow direction indicate the presence and extent of fibre orientation within the structure. For all samples, higher cutting forces were observed when cutting perpendicular to the flow direction than when cutting parallel to it, confirming the formation of anisotropic structures. These results suggest that the fibres maintain structural organisation within the protein–starch matrix. No significant differences in the anisotropy index were observed among the samples, with values ranging from 1.12 to 1.35.

The principal component analysis (PCA) showed that samples containing pea isolate and pea starch clustered within the same region and were associated with springiness, total dietary fibre (TDF), and starch (Figure 3). Samples supplemented with extruded pea hull fibre were located in the left upper quadrant, indicating that dietary fibre enhanced internal structuring, improved cohesiveness, which translated into increased chewiness. In contrast, the control sample (EP) was positioned on the positive side of PC1 and was associated with protein, fat, ash, hardness and, to a lesser extent, chewiness, suggesting a denser and mechanically stronger structure. The opposite positioning of starch and hardness along PC1 further indicates contrasting contributions of pea starch and extruded pea hull fibre to the textural characteristics of the extrudates.

Sensory evaluation

The use of legume-derived ingredients in extruded products alters the textural properties and sensory

attributes of the product. Scientific literature indicates that meat analogues produced from faba bean and pea flours tend to exhibit a more gummy texture and are more difficult to chew, although they may still possess a certain level of juiciness (Godschalk-Broers *et al.*, 2022; Knaapila *et al.*, 2024).

The samples were evaluated by expert assessors, as the aim of the study was not to determine consumer acceptance, but rather to assess the effect of dietary fibre on the structural and mechanical properties of the products. The obtained results will be useful for future research and development of meat analogue semi-finished or ready-to-eat products. When evaluating the experimental samples in terms of hardness, elasticity, fibrousness, gummy structure, colour, legume aroma and taste, as well as the intensity of bitter taste, the greatest differences were observed between the samples containing 10% and 15% dietary fibre and the other samples. The results for the intensity of the sensory attributes are presented in Figure 4.

The addition of extruded pea hulls above 5% increased the hardness of the samples, and their structure differed markedly from that of samples containing pea starch or potato starch. The EP sample exhibited the highest elasticity. In contrast, the lowest elasticity was observed in the EP-S-F5, EP-S-F10, and EP-S-F15 samples. The sample containing pea starch formed the least fibrous structure. However, the addition of 10% and 15% extruded pea fibre increased fibrousness. The gummy structure of the samples was evaluated during chewing. The results showed that none of the samples exhibited a strongly pronounced gummy sensation (values within the 2–5 range on the 9-point scale), although the perception of gummy structure increased with the addition of 10–15% dietary fibre.

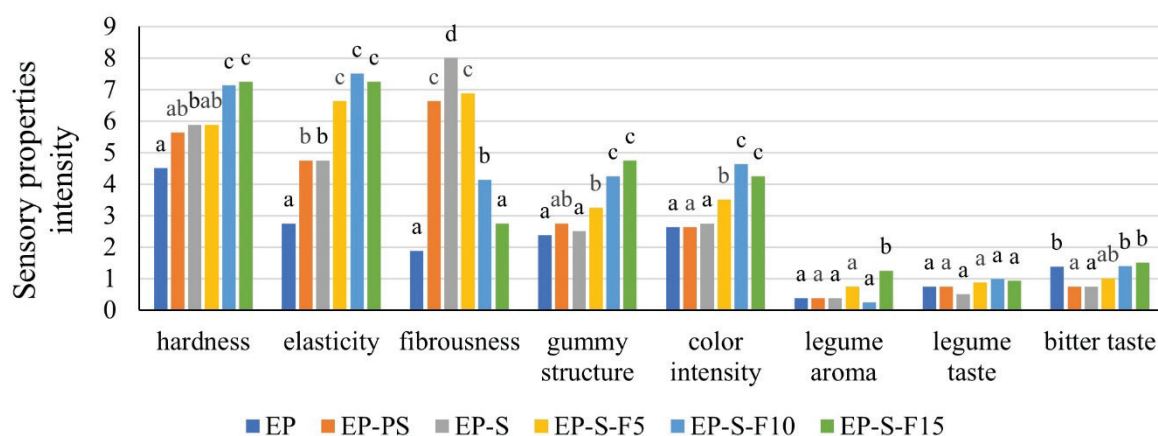


Figure 4. Sensory properties of the intensity of extruded samples.

EP – extruded pea protein isolate; EP-PS – extruded 80% pea protein isolate, 20% potato starch; EP-S – extruded 80% pea protein isolate, 20% pea starch; EP-S-F5 – 80% pea protein isolate, 15% pea starch, 5% pea hulls; EP-S-F10 – 80% pea protein isolate, 10% pea starch, 10% pea hulls; EP-S-F15 – 80% pea protein isolate, 5% pea starch, 15% pea hulls. Values not sharing a letter are statistically significantly different ($p < 0.05$).

The effect on colour was noticeable in the extruded samples containing 10% and 15% fibre, as extruded pea fibre has a greyish hue. In all analysed samples, the legume aroma and taste were weak, and no significant differences were observed among them. A slightly bitter taste was detected in all analysed samples. This attribute was less pronounced in the EP-S and EP-PS samples (0.75) compared with the EP-S-F10 and EP-S-F15 samples (1.4 and 1.5, respectively).

Relationship Between Composition and Sensory Properties

The sensory properties of extruded products are influenced by the composition of the raw materials. In meat analogue samples, one of the most important attributes is fibrousness, which is affected by the functional properties of starch and protein. The most pronounced fibre formation was observed in the EP-S sample containing pea starch. This can be explained by the relatively high amylose content in pea starch, which, according to the scientific literature, exceeds 30%, whereas in potato starch it is typically up to 30%. A higher amylose content promotes the formation of a denser and more mechanically stable gel structure. Such a gel dilutes the protein network in the product to a lesser extent, thereby promoting the development of a more pronounced fibrous structure. As a result, the extruded product becomes firmer and less elastic, and its perceived juiciness is reduced (Beniwal *et al.*, 2021).

In contrast, the addition of extruded pea hulls, which contain up to 75% insoluble dietary fibre, disrupts the stability of the starch-protein gel network, resulting in a reduction in fibrous structure intensity.

According to scientific research hydrogen bonding interactions between dietary fibre and proteins contribute to an increase in hardness within the gel-like structures of meat analogues (Chiang *et al.*, 2019; Rasul *et al.*, 2025).

For the further development and application of meat analogues, the aroma and taste of legumes, as well as the perception of bitterness, are important sensory attributes. Several studies report that products made from legume flours often exhibit a characteristic pea- or bean-like aroma and flavour. The aroma of legumes is primarily associated with aldehydes, alcohols, and sulphur compounds (Xu *et al.*, 2019). The perception of bitterness in legumes is also associated with other naturally occurring bioactive compounds, such as phenolic compounds, alkaloids, and saponins. Furthermore, several studies have demonstrated that peptides present in pea protein solutions are associated with different sensory attributes. Many of these peptides correlate with salty and broth-like flavours, suggesting a potential contribution to umami perception, whereas a smaller but still notable proportion has been linked to bitterness (Cosson *et al.*, 2022). These observations underline the important role of peptides as molecular contributors to taste perception in the oral cavity. In the present study, the legume flavour and aroma, as well as the intensity of bitter taste, were evaluated as low among all analysed samples (Chigwedere *et al.*, 2022; Xu *et al.*, 2019).

Relationship Between Textural Properties and Sensory Properties

Analysis of the results from instrumental measurements (hardness, springiness, and chewiness)

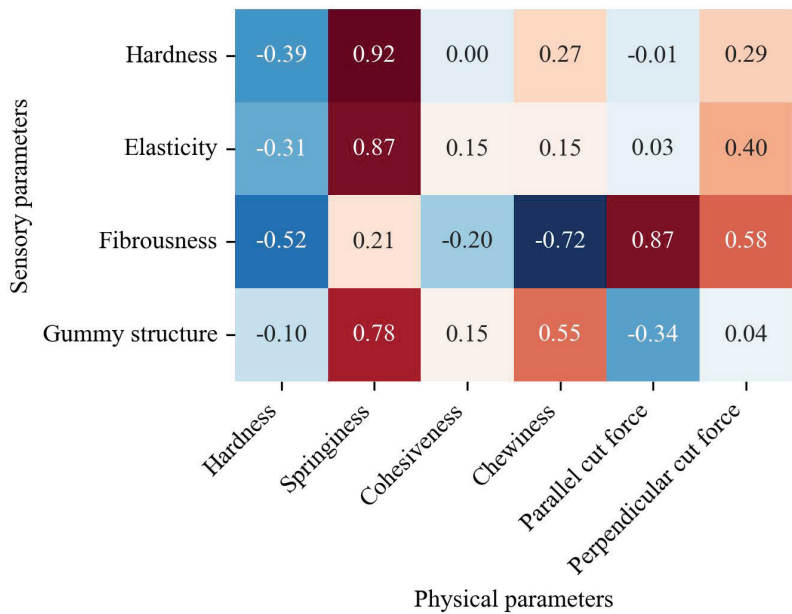


Figure 5. Correlation between physical and sensory parameters of extrudates.

and expert sensory evaluations revealed a negative correlation (-0.39) among the hardness values, but a weak positive correlation with perpendicular cutting force (Figure 5). Instrumental measurements indicated that hardness decreased with the addition of starch and dietary fibre; however, according to the expert assessments, the perceived hardness of the samples increased. This discrepancy may be related to the experts' expectations of a softer, juicier product texture. Similar observations were reported in the study by Knaapila *et al.* on the incorporation of oat dietary fibre β -glucans, where increasing water content improved mouthfeel and resulted in a more crumbly product structure (Knaapila *et al.*, 2024). However, water-holding capacity does not always directly affect a product's perceived juiciness and softness (Beniwal *et al.*, 2021).

The strong correlation between instrumental springiness and sensory parameters – hardness, elasticity and gummy texture – indicates that the well-developed network of proteins, starches and fibres is able to recover its shape after compression and is closely related to consumer perception of texture during chewing. Such extruded product structures exhibit resistance to compression and maintain structural integrity during chewing, resulting in higher perceived hardness, elasticity and gummy texture. The addition of dietary fibre further increased the perception of gumminess during chewing. This effect may be explained by the product's fat content: as fat content decreases, the gel structure becomes more pronounced, resulting in higher chewiness.

Conclusions

In high-moisture extrusion, pea starch and extruded pea hulls can serve as alternative raw materials for the production of meat analogues. The incorporation of up to 10% extruded fibre improved the product's structural properties, as evidenced by increased chewiness. The fibres became shorter but more pronounced, resulting in a softer texture and enhanced chewability. The use of protein isolate, pea starch, and extruded hulls in high-moisture extruded samples reduced the intensity of pea aroma, flavour, and bitterness. The results indicated that the textural properties and sensory characteristics of extruded pea protein-, starch-, and dietary fibre-based products made them suitable for the development of meat analogue products, as the structure is sufficiently fibrous and chewable, while the legume aroma and flavour remained relatively mild. These findings may offer practical insights for the creation of innovative food applications and the optimisation of future meat analogue products with high protein and fibre content.

Ethics statement

The sensory study received approval from the Ethics Committee of the Food Institute, Latvia University of Life Sciences and Technologies (No.7.1.3.-13.2/3 from 11.12.2025).

References

- AACC 74-09. (2000). *Measurement of Bread Firmness by Universal Testing Machine. Approved Methods of the American Association of Cereal Chemists*. AACC: St.Paul, Minesota, USA.
- Ahmad, D., Zhang, L., Gao, Y., Hu, Y., Deng, B., Tong, C., & Bao, J. (2025). Genotypic diversity and genome-wide association study of phosphorus content, amylose content, pasting, and textural properties of potato starch. *Carbohydrate Polymers*, 367(June), 123956. <https://doi.org/10.1016/j.carbpol.2025.123956>
- AOAC 985.29. (2023). *Total Dietary Fibre in Foods: Enzymatic-Gravimetric Method*.
- Beniwal, A. S., Singh, J., Kaur, L., Hardacre, A., & Singh, H. (2021). Meat analogs: Protein restructuring during thermomechanical processing. *Comprehensive Reviews in Food Science and Food Safety*, 20(2), 1221–1249. <https://doi.org/10.1111/1541-4337.12721>
- Bohrer, B. M. (2019). An investigation of the formulation and nutritional composition of modern meat analogue products. *Food Science and Human Wellness*, 8(4), 320–329. <https://doi.org/10.1016/j.fshw.2019.11.006>
- Chen, Q., Zhang, J., Zhang, Y., Kaplan, D. L., & Wang, Q. (2022). Protein-amylose/amylopectin molecular interactions during high-moisture extruded texturization toward plant-based meat substitutes applications. *Food Hydrocolloids*, 127(January), 107559. <https://doi.org/10.1016/j.foodhyd.2022.107559>
- Cheng, Z., Qiu, Y., Bian, M., He, Y., Xu, S., Li, Y., Ahmad, I., Ding, Y., & Lyu, F. (2024). Effect of insoluble dietary fiber on printing properties and molecular interactions of 3D-printed soy protein isolate-wheat gluten plant-based meats. *International Journal of Biological Macromolecules*, 258(P1), 128803. <https://doi.org/10.1016/j.ijbiomac.2023.128803>
- Chiang, J. H., Loveday, S. M., Hardacre, A. K., & Parker, M. E. (2019). Effects of soy protein to wheat gluten ratio on the physicochemical properties of extruded meat analogues. *Food Structure*, 19(November 2018). <https://doi.org/10.1016/j.foostr.2018.11.002>
- Chigwedere, C. M., Wanasundara, J. P. D., & Shand, P. J. (2022). Sensory descriptors for pulses and pulse-derived ingredients: Toward a standardized lexicon

- p and sensory wheel.
- Comprehensive Reviews in Food Science and Food Safety*
- , 21(2), 999–1023.
- <https://doi.org/10.1111/1541-4337.12893>
- Cosson, A., Oliveira Correia, L., Descamps, N., Saint-Eve, A., & Souchon, I. (2022). Identification and characterization of the main peptides in pea protein isolates using ultra high-performance liquid chromatography coupled with mass spectrometry and bioinformatics tools. *Food Chemistry*, 367(July 2021), 130747. <https://doi.org/10.1016/j.foodchem.2021.130747>
- De Angelis, D., Kaleda, A., Pasqualone, A., Vaikma, H., Tamm, M., Tammik, M. L., Squeo, G., & Summo, C. (2020). Physicochemical and sensorial evaluation of meat analogues produced from dry-fractionated pea and oat proteins. *Foods*, 9(12). <https://doi.org/10.3390/foods9121754>
- Foley, J. D., Czaja, T. P., Rieckmann, M. M., Dervishi, M., Engelsens, S. B., Laursen, K. H., Bononad-Olmo, A., Bredie, W. L. P., & Orlie, V. (2025). Cultivar selection and processing methods are crucial tools for tailoring the physico-chemical properties and functionality of pea (*Pisum sativum* L.) protein ingredients. *Current Research in Food Science*, 11(September). <https://doi.org/10.1016/j.crfs.2025.101218>
- Gasparre, N., van den Berg, M., Oosterlinck, F., & Sein, A. (2022). High-Moisture Shear Processes: Molecular Changes of Wheat Gluten and Potential Plant-Based Proteins for Its Replacement. *Molecules*, 27(18), 1–24. <https://doi.org/10.3390/molecules27185855>
- Godschalk-Broers, L., Sala, G., & Scholten, E. (2022). Meat Analogues: Relating Structure to Texture and Sensory Perception. *Foods*, 11(15). <https://doi.org/10.3390/foods11152227>
- Gutöhrlein, F., Morales-Medina, R., Boje, A. L., Drusch, S., & Schalow, S. (2020). Modulating the hydration properties of pea hull fibre by its composition as affected by mechanical processing and various extraction procedures. *Food Hydrocolloids*, 107(April). <https://doi.org/10.1016/j.foodhyd.2020.105958>
- Horstmann, S. W., Belz, M. C. E., Heitmann, M., Zannini, E., & Arendt, E. K. (2016). Fundamental study on the impact of gluten-free starches on the quality of gluten-free model breads. *Foods*, 5(2), 1–12. <https://doi.org/10.3390/foods5020030>
- ISO. (2024). *ISO 10520:1997 Native starch — Determination of starch content — Ewers polarimetric method*. ISO: Geneva, Switzerland, 2024.
- Jakhjoukh, S., Van Hecke, M., Skirtach, A. G., Eeckhout, M., & Rolandelli, G. (2026). Improvement of physicochemical and textural properties of soy-based meat analogues by the addition of potato starch: Relationships with the secondary structure of proteins. *Innovative Food Science and Emerging Technologies*, 108 (December 2025), 1–9. <https://doi.org/10.1016/j.ifset.2025.104424>
- Jebalia, I., Maigret, J. E., Réguerre, A. L., Novales, B., Guessasma, S., Lourdin, D., Della Valle, G., & Kristiawan, M. (2019). Morphology and mechanical behaviour of pea-based starch-protein composites obtained by extrusion. *Carbohydrate Polymers*, 223(April), 115086. <https://doi.org/10.1016/j.carbpol.2019.115086>
- Jia, R., Cui, C., Gao, L., Qin, Y., Ji, N., Dai, L., Wang, Y., Xiong, L., Shi, R., & Sun, Q. (2023). A review of starch swelling behavior: Its mechanism, determination methods, influencing factors, and influence on food quality. *Carbohydrate Polymers*, 321(April). <https://doi.org/10.1016/j.carbpol.2023.121260>
- Johansson, M., Nilsson, K., & Wendin, K. (2026). *Pea Starch and Pea Fiber — A Review of Functional Properties, Sensory Characteristics, and Value-Added Uses*. <https://doi.org/10.1111/1541-4337.70419>
- Kaleda, A., Talvistu, K., Vaikma, H., Tammik, M. L., Rosensvald, S., & Vilu, R. (2021). Physicochemical, textural, and sensorial properties of fibrous meat analogs from oat-pea protein blends extruded at different moistures, temperatures, and screw speeds. *Future Foods*, 4, 100092. <https://doi.org/10.1016/j.fufo.2021.100092>
- Kantanen, K., Oksanen, A., Edelmann, M., Suhonen, H., Sontag-Strohm, T., Piironen, V., Diaz, J. M. R., & Jouppila, K. (2022). Physical Properties of Extrudates with Fibrous Structures Made of Faba Bean Protein Ingredients Using High Moisture Extrusion. *Foods*, 11(9), 1–17. <https://doi.org/10.3390/foods11091280>
- Kirse-Ozolins, A., Muizniece-Brasava, S., & Veipa, J. (2019). *Effect of various packaging solutions on the quality of hazelnuts in nut-dried fruit mixes. Table 2*, 216–221. <https://doi.org/10.22616/foodbalt.2019.007>
- Klava, D., Galoburda, R., Gramatina, I., Straumite, E., Staugis, A., & Reidzane, S. (2024). Effect of the Extruded Pea Hulls on Physicochemical and Sensory Properties of Wheat Bread. *Foods*, 13, 3985. <https://doi.org/10.3390/foods13243985>
- Knaapila, A., Kantanen, K., Ramos-Diaz, J. M., Piironen, V., Sandell, M., & Jouppila, K. (2024). Sensory and Physical Properties of Fibrous Meat Analogs Made from Faba Bean, Pea, and Oat Using High-Moisture Extrusion. *Foods*, 13(10), 1–14. <https://doi.org/10.3390/foods13101444>

- Marczak, A., & Mendes, A. C. (2024). Dietary Fibers: Shaping Textural and Functional Properties of Processed Meats and Plant-Based Meat Alternatives. *Foods*, 13(12). <https://doi.org/10.3390/foods13121952>
- Mir, S. A., Manickavasagan, A., & Shah, M. A. (Eds.). (2019). *Whole grains. Processing, product development and nutrition aspects*. CRC Press: Boca Raton, FL, USA, 2019.
- Plattner, B. J., Hong, S., Li, Y., Talavera, M. J., Dogan, H., Plattner, B. S., & Alavi, S. (2024). Use of Pea Proteins in High-Moisture Meat Analogs: Physicochemical Properties of Raw Formulations and Their Texturization Using Extrusion. *Foods*, 13(8), 1–23. <https://doi.org/10.3390/foods13081195>
- Ramirez, C. S. V., Temelli, F., & Saldaña, M. D. A. (2021). Production of pea hull soluble fiber-derived oligosaccharides using subcritical water with carboxylic acids. *Journal of Supercritical Fluids*, 178(July). <https://doi.org/10.1016/j.supflu.2021.105349>
- Ramos Diaz, J. M., Kantanen, K., Edelmann, J. M., Suhonen, H., Sontag-Strohm, T., Jouppila, K., & Piironen, V. (2022). Fibrous meat analogues containing oat fiber concentrate and pea protein isolate: Mechanical and physicochemical characterization. *Innovative Food Science and Emerging Technologies*, 77(February), 102954. <https://doi.org/10.1016/j.ifset.2022.102954>
- Rasul, S., Thaivalappil, A., Asiz, A., Maymanah, Y., Faiz, M., Muhd, B., Abdullah, F., Tarique, M., Zubair, M., Hong, J., & Yuliarti, O. (2025). Unveiling the potential of insoluble dietary fiber from by-products in structural advancements of plant-based meat analogues. *Future Foods*, 12(November), 100839. <https://doi.org/10.1016/j.fufo.2025.100839>
- Ratnayake, W. S., Hoover, R., Shahidi, F., Perera, C., & Jane, J. (2001). Composition, molecular structure, and physicochemical properties of starches from four field pea (*Pisum sativum* L.) cultivars. *Food Chemistry*, 74(2), 189–202. [https://doi.org/10.1016/S0308-8146\(01\)00124-8](https://doi.org/10.1016/S0308-8146(01)00124-8)
- Regulation, E. (2006). Regulation (EC) No 1924/2006 of the European parliament and of the council of 20 December 2006 on nutrition and health claims made on foods. *Official Journal of European Union*, L 404/9.
- Schmid, E. M., 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>
- Sha, L., & Xiong, Y. L. (2020). Plant protein-based alternatives of reconstructed meat: Science, technology, and challenges. *Trends in Food Science and Technology*, 102(June), 51–61. <https://doi.org/10.1016/j.tifs.2020.05.022>
- Tachie, C., Nwachukwu, I. D., & Aryee, A. N. A. (2023). Trends and innovations in the formulation of plant-based foods. *Food Production, Processing and Nutrition*, 5(1). <https://doi.org/10.1186/s43014-023-00129-0>
- Theng, A. H. P., Tarique, M., Ong, D. S. M., Chiang, J. H., Rasul, S., & Yuliarti, O. (2025). Evaluating the effects of insoluble dietary fibres on pea protein-based extruded meat analogues. *International Journal of Biological Macromolecules*, 311(P1), 143715. <https://doi.org/10.1016/j.ijbiomac.2025.143715>
- Ubaid, M., Ahmed, M., Sheikh, M. A., Jan, T., Sheikh, I., Ahmed, N., Kumar, K., Kumar, A., & Vashisht, A. (2026). Potato starch as a next-generation biopolymer: Functionality, modification, sustainability, and industrial perspectives. *Food Physics*, 3(October 2025), 100082. <https://doi.org/10.1016/j.foodp.2026.100082>
- Van der Sman, R. G. M., & Van der Goot, A. J. (2023). Hypotheses concerning structuring of extruded meat analogs. *Current Research in Food Science*, 6(March), 100510. <https://doi.org/10.1016/j.crfs.2023.100510>
- Wagner, C. E., & Ganjyal, G. M. (2024). Impact of functional dietary fiber incorporation on the appearance and mechanical properties of extruded high moisture meat analogs. *Journal of Food Science*, 89(8), 4953–4968. <https://doi.org/10.1111/1750-3841.17164>
- 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). <https://doi.org/10.3390/foods10010102>
- Wu, D. T., Li, W. X., Wan, J. J., Hu, Y. C., Gan, R. Y., & Zou, L. (2023). A Comprehensive Review of Pea (*Pisum sativum* L.): Chemical Composition, Processing, Health Benefits, and Food Applications. *Foods*, 12(13), 1–40. <https://doi.org/10.3390/foods12132527>
- Xu, M., Jin, Z., Lan, Y., Rao, J., & Chen, B. (2019). HS-SPME-GC-MS/olfactometry combined with chemometrics to assess the impact of germination on flavor attributes of chickpea, lentil, and yellow pea flours. *Food Chemistry*, 280(December 2018), 83–95. <https://doi.org/10.1016/j.foodchem.2018.12.048>
- Yang, Y., Zheng, Y., Ma, W., Zhang, Y., Sun, C., & Fang, Y. (2023). Meat and plant-based meat

- analogs: Nutritional profile and in vitro digestion comparison. *Food Hydrocolloids*, 143(December 2022), 108886. <https://doi.org/10.1016/j.foodhyd.2023.108886>
- Zhang, S., Zhang, R., Hu, Y., Chen, H., Chen, W., Zhang, M., Liu, H., Liu, S., Pei, J., & Gao, S. (2025). Structural and physicochemical properties of pea starch dual-treated with dry heating and galactomannans. *International Journal of Biological Macromolecules*, 294(September 2024), 139374. <https://doi.org/10.1016/j.ijbiomac.2024.139374>
- Zhang, X., Shen, A., Zhang, Z., Zhang, T., Jiang, L., Zhou, W., Zhang, Y., & Sui, X. (2024). Advancing molecular understanding in high moisture extrusion for plant-based meat analogs: Challenges and perspectives. *Food Chemistry*, 460(P1), 140458. <https://doi.org/10.1016/j.foodchem.2024.140458>

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