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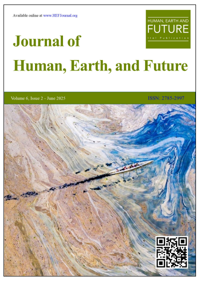

Optimisation of Extrusion Process Parameters for Producing Combined Breakfast Cereals Using Pumpkin Flour

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Abstract

The extrusion process plays a key role in the production of dry breakfast cereals, providing improved organoleptic properties, structure, and nutritional value. In recent decades, this method has been actively used in the food industry due to its high efficiency and ability to modify the physicochemical characteristics of raw materials. The aim of this study is to optimise the process parameters of extrusion in the production of combined dry breakfast cereals with added pumpkin flour. For this purpose, the Box–Behnken rotational experimental design method and regression analysis were used to assess the effect of temperature (130–170°C), raw material moisture (10%–18%), and screw speed (180–300 rpm) on the quality indicators of the extruded product. At 170°C, a raw material moisture of 18%, and a screw speed of 180–210 rpm, a product with low bulk density, high expansion coefficient, and optimal water absorption and solubility indicators was formed. The best technological characteristics were achieved at 170°C, 18% humidity, and 210 rpm, providing an expansion coefficient of 3.8, a water absorption index of 3.2 g/g, a water solubility index of 2.2%, a bulk density of 0.43 g/cm³, and a β-carotene content of 5.9 mg/100 g. Adding pumpkin flour positively affected the functional value of extrudates, increasing the dietary fibre, β-carotene, and antioxidant contents. However, introducing more than 15% pumpkin decreased the expansion coefficient and increased the bulk density due to changes in the moisture content and viscosity of the mixture. The novelty of the study lies in the scientific substantiation of the optimal extrusion parameters with added pumpkin flour for the development of functional breakfast cereals with improved nutritional and organoleptic characteristics, helping to expand the range of healthy food products.

Keywords: Extrusion; Breakfast Cereals; Optimal Parameters; Beta-Carotene; Texture Improvements.

1. Introduction

The extrusion process is widely used in the food industry to produce various products, including breakfast cereals. One promising area is the development of combined breakfast cereals using alternative plant ingredients, such as pumpkin flour. Pumpkin flour is a valuable source of dietary fibre, vitamins, and antioxidants, making it a useful component in functional foods [1]. However, achieving optimal product quality requires careful adjustment of extrusion parameters, such as temperature, raw material moisture, and screw speed, which significantly affect the texture, taste, and nutritional value of the final product [2, 3]. Extrusion is a process in which mixtures of various ingredients pass through an extruder, where they are changed by temperature, pressure, and mechanical processing, forming a new

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product. This process not only improves the textural properties of the product but also increases its biological value due to the activation of biochemical processes such as protein denaturation and partial destruction of cell walls. This work studies the influence of extrusion process parameters on the physicochemical properties of combined breakfast cereals with the addition of pumpkin flour. Particular attention is paid to optimising the extrusion conditions to ensure high product quality while maintaining functional properties. Such studies help expand the range of functional food products and use local plant materials, which is important for sustainable development in the food industry [4].

Additionally, studies show that using pumpkin flour in extrusion processes can help improve textural characteristics and increase the dietary fibre content of the product, which is especially important for consumers interested in healthy eating [5, 6]. Adding alternative plant ingredients, such as pumpkin flour, helps reduce production costs due to the use of available raw materials and reduced dependence on traditional ingredients [7]. Hence, it is important to optimise technological processes to increase the competitiveness of food products in the market. The physicochemical and sensory characteristics of products such as breakfast cereals can be optimised by extrusion, provided that the extrusion parameters, including temperature, screw speed, and raw material moisture content, are properly adjusted [6-8]. Earlier studies have shown that extrusion conditions can significantly affect the coefficient of expansion, water absorption, and solubility of products, which are critical for breakfast cereals [7, 9].

Other works have confirmed this, demonstrating that the extrusion parameters determine the physical properties and nutritional profile of gluten-free cassava flakes [8-10]; optimising these properties can improve the consumer acceptability of the product. Purple hull-less barley is a promising ingredient for extruded breakfast cereals, combining high nutritional value with improved functional properties [10, 11]. These studies have shown that extrusion affects parameters such as density, hardness, and expansion coefficient while maintaining significant antioxidant activity. Adding barley bran to refined wheat flour significantly increased the antioxidant activity of extrudates and decreased their estimated glycaemic index, making such products more popular for a healthy diet. However, due to its universal technological characteristics, wheat remains one of the key ingredients in the production of a wide range of ready-to-eat food products. Extrusion is a method that not only modifies the structural and functional characteristics of wheat products but also optimises their nutritional value [10-12].

In addition, the study emphasises that extrusion can help create products with improved sensory characteristics and increased nutrient bioavailability, which are especially important for developing functional and specialised foods. Adding defatted flaxseed flour to the formulation of brown rice-based snacks has been shown to contribute to a significant increase in the content of protein, fat, ash, and bioactive compounds, such as phenols and flavonoids, which improve their antioxidant properties [10, 13].

Pumpkin (*Cucurbita moschata* L.) is an important vegetable due to its high nutritional value and beneficial properties. It is a rich source of carotenoids (α- and β-carotene), which give it a yellow or orange colour [14, 15]. Pumpkin flour is a source of beneficial microelements, such as vitamins A, E, and B, and also has a high content of vegetable proteins and fibre. Such properties make it a valuable ingredient for improving the nutritional value of combination products. Adding pumpkin flour to breakfast cereals has been shown to improve their texture and nutritional value, with optimal extrusion parameters playing a key role in ensuring the high quality of the final product [16, 17]. In addition, pumpkin flour helps improve water absorption and solubility in water, making the product easier to consume and increasing its nutritional value. However, during extrusion, it is important to consider that excess moisture or temperatures above 160°C can lead to deterioration of the structure and the loss of a significant portion of nutrients [18, 19].

Optimising the extrusion conditions in the production of combined breakfast cereals with added pumpkin is a multi-parameter task that requires consideration of the interactions of various factors. The correct selection of process parameters will yield a product with high organoleptic and nutritional properties that meets the needs of consumers interested in healthy nutrition.

Adding pumpkin flour helps create products with a natural and rich taste, which is especially important in the context of the growing demand for organic and environmentally friendly products [20, 21]. Consumers increasingly prefer functional products with high natural vitamin, mineral, and antioxidant contents, which positively affect health. Including pumpkin flour in extruded products not only increases their nutritional value but also adds natural sweetness and pleasant colour, improving the organoleptic characteristics of the products.

Using local resources, such as pumpkin flour, helps reduce the carbon footprint of production, as it reduces the need to import expensive ingredients and transport raw materials over long distances. This is consistent with the principles of sustainable development and meets modern trends towards the localisation of food chains. In addition, processing pumpkin into flour effectively minimises food waste, which is especially important in waste-free production. In the agro-industrial complex, a significant amount of vegetable raw material remains unused. However, processing technologies allow the use of almost all parts of the pumpkin, including the peel and seeds, which significantly reduces the level of waste and increases the cost-effectiveness of production. Moreover, pumpkin flour-based products can become an important part of a strategy to reduce food losses and create a more balanced and environmentally friendly diet. Further research in this area could be aimed at developing optimal methods for processing pumpkins that preserve the maximum amount of biologically active compounds, as well as studying the influence of extrusion parameters on the preservation of nutrients in the final product.

2. Material and Methods

The raw materials were purchased from local manufacturers in various regions of Kazakhstan, ensuring environmental friendliness, quality, and availability. The corn groats were purchased from the processing plant of PartnerAgro LLP, located in Shymkent (Turkestan). The company specialises in processing corn grown on irrigated land in southern Kazakhstan. This region is characterised by favourable climatic conditions for growing corn, ensuring a high starch content and stable physicochemical properties.

The rice flour was purchased from a local manufacturer (Nai-Mir LLP) in the Kyzylorda region. The rice used for flour production was grown in the Shieli district, which is known for its rice farming traditions. The Marjan rice variety used has a high degree of gelatinisation, crucial for forming extrudates with a porous structure and pleasant texture.

The pumpkin flour was made from the 'Vostochnaya' and 'Titan' varieties, grown in the Almaty and Zhambyl regions, respectively. The pumpkins were purchased from the Agrofarm Zhetisu LLP farm, located in the Talgar district of the Almaty region. The pumpkins from this region are known for their high β-carotene, pectin, and mineral content, which make them an ideal ingredient for functional foods. The pumpkin flour was produced by low-temperature drying and grinding, which preserves the biologically active substances.

Water conforming to the quality standards of the Republic of Kazakhstan was used to moisten the mixture. The water was obtained from a five-stage filter, with parameters corresponding to GOST RK 2874-2016 (drinking water).

A detailed selection of raw materials, considering their quality, regional characteristics, and environmental friendliness, provided the basis for producing high-quality extruded breakfast cereals. The use of ingredients produced in Kazakhstan highlights the local character of the production and contributes to the development of the domestic agro-industrial sector.

The mixture was based on corn groats (50%), rice (25%), and pumpkin flour (24%). Pumpkin flour was used as a source of carotenoids and dietary fibre, which enhanced the functional value of the product. Salt and sugar (1%) were added to improve the taste characteristics. The raw materials were mixed until a homogeneous mass was obtained, after which its moisture content was adjusted to 10%–18% (depending on the experimental conditions).

Adding pumpkin flour above the 15% threshold can significantly change the physicochemical properties of the product. Such changes can be beneficial: they include a higher β-carotene, antioxidant, and dietary fibre content, which enhances the functional properties of the product; improved antioxidant status due to the increased amount of polyphenols and vitamin E, which are good for health; and a high fibre concentration that slows down the absorption of carbohydrates, reducing blood sugar spikes. This product is suitable for diabetics and people who control their glucose levels. Finally, added pumpkin flour improves the colour and appearance of the product due to the high concentration of β-carotene (which has an intense yellow/orange hue).

Additional studies were conducted because this breakfast food exceeded the 15% threshold. Barrier packaging was used to protect the product from moisture, oxygen, and light. Combining pumpkin flour with other plant ingredients (rice flour) improved the texture and yield. Thus, exceeding the 15% threshold requires additional technological adaptation, but it can create a unique functional product with high nutritional value. Although pumpkin flour improves the nutritional value of cereals, its industrial use is associated with seasonality, logistical difficulties, variable quality, and high cost.

Key solutions:

- Optimisation of procurement and creation of stock.
- Implementation of energy-efficient processing technologies.
- Use of antioxidants to extend shelf life.
- Combination with alternative plant ingredients.

Thus, successful integration of pumpkin flour into mass production of cereals is possible, but it requires competent resource management, contract logistics and technological optimisation.

Figure 1 shows the flow chart of the proposed workflow.

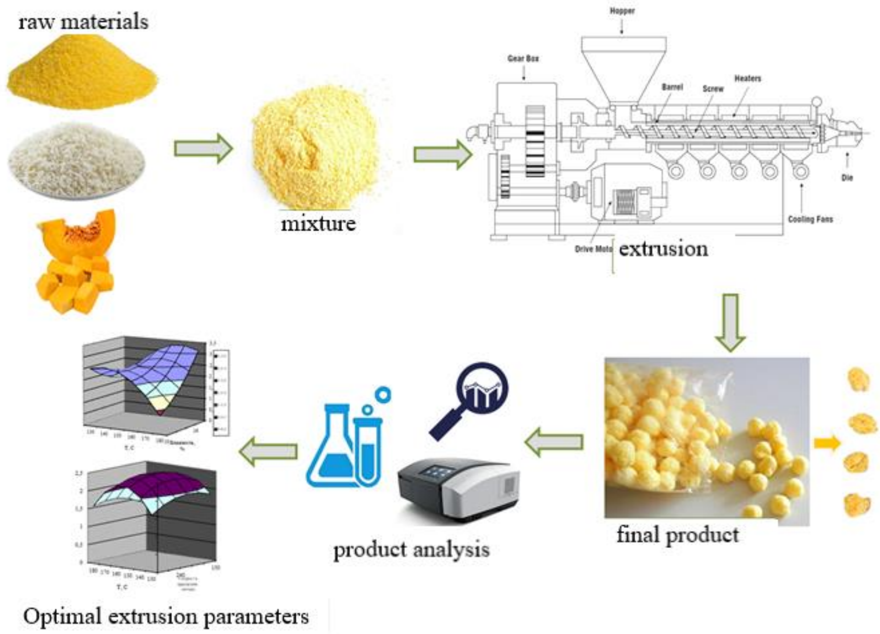

Figure 1. Workflow

Extrusion was performed using a single-screw extruder. The main parameters were varied: the extrusion zone temperature ranged from 130 to 170°C, the raw material moisture content ranged from 10% to 18%, and the screw rotation speed ranged from 180 to 300 rpm. The Box–Behnken method was used to determine the optimal conditions. This method builds a mathematical model of the process and identifies the effect of the extrusion parameters on the product quality.

Experiments were conducted according to the Box–Behnken design to analyse the effects of temperature, humidity, and screw velocity on the physicochemical characteristics of the extruded product. As a result, the following data were obtained: expansion coefficient (ER), water absorption index (WAI), water solubility index (WSI), bulk density (BD), and β-carotene content (β).

The ER was calculated using a CLEKAHO digital calliper with an accuracy of 0.01 mm. The BD of the extruded snacks (g/cm^3) was determined by dividing the mass by the volume, assuming the extrudate was cylindrical.

A small amount of the flour (2 g) intended for extrusion was weighed, placed in 25 mL of distilled water, and left to stand for 30 minutes. Subsequently, it was carefully mixed. The mixture was centrifuged (low-speed desktop centrifuge L-530, China) at 3000 ×g for 15 minutes. The filler liquid was poured into an evaporation cup of known weight and allowed to stand for 3 hours at 105°C. WAI is defined as the ratio of the mass of the gel remaining after removing the filler liquid to the mass of the initial dry substance (Equation 1). According to Equation 2, WSI is the dry matter in the filler fluid, expressed as a percentage of the initial sample [22].

$$\text{WAI (g/g)} = \frac{\text{Weight gain in the gel}}{\text{Dry mass of the extrudate}} \quad (1)$$

$$\text{WSI (\%)} = \frac{\text{Mass of dry matter in the filler fluid}}{\text{Dry mass of the extrudate}} \times 100 \quad (2)$$

The carotenoid content was determined according to FS 42-3192-95. Briefly, exactly 0.05 g of the product was placed in a 0.1 dm^3 flask and dissolved, stirring thoroughly, in alcohol preheated to 40°C. Then, the optical density of the sample was measured in a cuvette with a layer thickness of 0.01 cm using a spectrophotometer (Figure 2) at a wavelength of 0.45 microns. The reference solution was the same solvent. The contents of the flask were cooled to 20°C, the volume of the solution in the flask was adjusted to the mark using alcohol, and it was mixed thoroughly.

The total content of carotenoids in mg % (X) (in terms of β-carotene) was calculated using Equation 3:

$$x = \frac{D\ .\ 100\ .\ 100\ .\ 10}{a\ .\ 2500} \quad (3)$$

where D is the optical density of the solution of the test sample, a is the weight in grams, 100 represents the dilution in mL, 2500 is the Th extinction (the specific absorption index of β-carotene in alcohol at a wavelength of 450 nm), and 10 is the amount of β-carotene in 1 mL of 1% alcohol in mg.

A rotatable second-order plan (Box plan) was used to obtain a mathematical model of the technological process (i.e. a regression equation). Based on the experimental studies of the process, temperature, moisture content, and screw rotation speed (x_1, x_2, x_3) were chosen as the factors influencing the optimisation criteria. Next, the intervals and levels of variation of the input parameters were encoded, as shown in Table 1.

Table 1. Encoding of intervals and levels of variation of input factors

Factors		Levels of variation					Variation intervals
Natural	Coded	*−1.68*	*−1*	*0*	*+1*	*+1.68*	
Temperature	x_1	130	140	150	160	170	10
Moisture content	x_2	10	12	14	16	18	2
Screw rotation speed	x_3	180	210	240	270	300	30

Encoding standardised the analysis of factors and their interactions using normalised values (−1.68, −1, 0, +1, +1.68). This helped identify the optimal extrusion conditions for manufacturing combined breakfast cereals with pumpkin flour.

3. Results

Table 2 presents the planning matrix for the study of the effects of extrusion conditions (temperature, moisture content, and screw speed) on the physicochemical characteristics of the extruded product based on a mixture of corn, rice, and pumpkin flour. The following factors were considered: extrusion temperature (°C), raw material moisture content (%), and screw speed (rpm). The expansion coefficient (ER), WAI, WSI, BD, and β-carotene content were recorded.

Table 2. Rotatable planning matrix for investigating the experimental process

No	Encoded values			Natural values			Experimental values				
	x_1	x_2	x_3	*Temperature, °C*	*Raw material moisture (%)*	*Screw speed (rpm)*	*ER*	*WAI*	*WSI*	*BD*	*β*
1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***
1	−1	−1	−1	160	16	270	2.5	2.3	1.5	0.46	3.5
2	−1	−1	1	160	16	210	3.0	2.1	1.6	0.47	3.6
3	−1	1	−1	160	12	270	3.1	2.0	1.7	0.49	4.1
4	−1	1	1	160	12	210	3.3	2.0	1.5	0.46	4.0
5	1	−1	−1	140	16	270	3.2	2.1	1.6	0.45	4.4
6	1	−1	1	140	16	210	3.4	2.3	1.7	0.45	4.6
7	1	1	−1	140	12	270	3.6	2.7	1.6	0,46	4.3
8	1	1	1	140	12	210	3.8	2.5	1.5	0.43	4.5
9	−1.68	0	0	140	14	240	3.5	2.5	1.8	0.44	4.9
10	1.68	0	0	160	14	240	3.8	2.3	1.9	0.50	4.5
11	0	−1.68	0	150	10	240	3.5	2.5	1.8	0.45	4.9
12	0	1.68	0	150	18	240	3.9	2.9	2.0	0.51	5.2
13	0	0	−1.68	150	14	180	3.6	2.7	1.9	0.49	4.5
14	0	0	1.68	150	14	300	3.6	2.6	1.8	0.47	4.6
15	1.68	1.68	−1.68	170	18	180	3.6	2.6	1.8	0.48	5.6
16	1.68	1	−1	170	16	210	3.5	2.5	1.6	0.51	5.7
17	1.68	0	0	170	14	240	3.1	2.5	1.8	0.48	4.2
18	1.68	−1	+1	170	12	270	3.1	2.8	1.9	0.51	3.7
19	1.68	−1.68	1.68	170	10	300	3.5	2.7	1.9	0.50	3.2

Table 3 shows the confidence intervals of the process optimisation criteria.

Table 3. Confidence intervals of the optimisation criteria

Physicochemical characteristics		Input parameter	Confidence intervals			
			Δb_0	Δb_i	Δb_{ii}	Δb_{ij}
Expansion coefficient	ER	y_1	±0.22	±0.15	±0.14	±0.19
Water absorption index	WAI	y_2	±0.12	±0.08	±0.07	±0.00
Water solubility index	WSI	y_3	±0.06	±0.04	±0.04	±0.05
Bulk density	BD	y_4	±0.04	±0.03	±0.03	±0.04
β-carotene content	β	y_5	±0.88	±0.59	±0.57	±0.77

By comparing the confidence intervals from Table 3 with the corresponding regression coefficients in Table 4, the interaction effects of the input factors are insignificant.

Table 4. Coefficients of regression equations of output parameters

Optimisation criteria	Coefficients	Process
1	**2**	**3**
	With encoded values of the factors	
	b_0	2.832084192
	b_1	0.190613
	b_2	0.17363
	b_3	0.08052
	b_{12}	−0.0125
	b_{13}	−0.0375
	b_{23}	−0.0375
	b_{11}	0.195269
	b_{22}	0.212909
	b_{33}	0.177629
Expansion coefficient	***For natural values of the factors***	
	B_0	55.9371
	B_1	−0.528
	B_2	−1.1598
	B_3	−0.06455
	B_{12}	−0.000625
	B_{13}	−0.000125
	B_{23}	−0.00063
	B_{11}	0.001953
	B_{22}	0.053227
	B_{33}	0.000197
	F_p	2.37022
	With encoded values of the factors	
	b_0	2.485371344
	b_1	0.063245
	b_2	0.127661
	b_3	−0.03924
	b_{12}	0.15
	b_{13}	0.025
	b_{23}	−0.025
	b_{11}	−0.1096
	b_{22}	0.066802
	b_{33}	−0.03904
Water absorption index	***For natural values of the factors***	
	B_0	−5.5777
	B_1	0.210118
	B_2	−1.42878
	B_3	0.012846
	B_{12}	0.0075
	B_{13}	8.333
	B_{23}	−0.00042
	B_{11}	−0.00109598
	B_{22}	0.016700512
	B_{33}	−4.33755
	F_p	8.08191404

	With encoded values of the factors	
	b_0	1.593045712
	b_1	0.019618
	b_2	0.017275
	b_3	−0.05651
	b_{12}	−0.0375
	b_{13}	0.0125
	b_{23}	−0.0625
	b_{11}	0.041513
	b_{22}	0.059153
	b_{33}	−0.01141
Water solubility index	***For natural values of the factors***	
	B_0	7.2012
	B_1	−0.10633
	B_2	0.125819
	B_3	0.012534
	B_{12}	−0.001875
	B_{13}	4.167×10^{-5}
	B_{23}	−0.00104
	B_{11}	0.000415
	B_{22}	0.014788
	B_{33}	-1.3×10^{-5}
	F_p	8.69832
	With encoded values of the factors	
	b_0	0.529428395
	b_1	0.000791
	b_2	0.008111
	b_3	−0.00243
	b_{12}	−0.00375
	b_{13}	−0.00125
	b_{23}	−0.00875
	b_{11}	−0.02522
	b_{22}	−0.02169
	b_{33}	−0.0164
Bulk density	***For natural values of the factors***	
	B_0	−8.3414
	B_1	0.079372
	B_2	0.219042
	B_3	0.011334
	B_{12}	−0.000188
	B_{13}	−4.17
	B_{23}	−0.00015
	B_{11}	−0.00025
	B_{22}	−0.00542
	B_{33}	−1.85
	F_p	0.398102434

β-carotene content	***With encoded values of the factors***	
	b_0	4.343117648
	b_1	0.14113
	b_2	0.095453
	b_3	0.041578
	b_{12}	−0.15
	b_{13}	0.05
	b_{23}	−0.025
	b_{11}	−0.00927
	b_{22}	0.114212
	b_{33}	−0.062187584
	For natural values of the factors	
	B_0	−10.3934
	B_1	0.106916
	B_2	0.473239
	B_3	0.015386
	B_{12}	−0.0075
	B_{13}	0.0001667
	B_{23}	−0.00042
	B_{11}	-9.267×10^{-5}
	B_{22}	0.028553
	B_{33}	-6.9×10^{-5}
	F_p	0.356077

Thus, the regression equations for the physicochemical characteristics of the extruded products for the encoded values take the following forms:

$$y_1 = 2.832084192 + 0.190613x_1 + 0.17363x_2 + 0.08052x_3 - 0.0125x_1x_2 - 0.0375x_1x_3 - 0.0375x_2x_3 + 0.195269x_1^2 + 0.212909x_2^2 + 0.177629x_3^2$$

$$y_2 = 2.485371344 + 0.063245x_1 + 0.127661x_2 - 0.03924x_3 + 0.15\, x_1x_2 - 0.025\, x_1x_3 - 0.025x_2x_3 - 0.1096x_1^2 + 0.066802x_2^2 - 0.03904x_3^2$$

$$y_3 = 1.593045712 + 0.019618x_1 + 0.017275x_2 - 0.05651x_3 - 0.0375x_1x_2 + 0.0125x_1x_3 - 0.0625\, x_2x_3 + 0.041513x_1^2 + 0.059153x_2^2 - 0.01141x_3^2$$

$$y_4 = 0.529428395 + 0.000791x_1 + 0.008111x_2 - 0.00243x_3 - 0.00375\, x_1x_2 - 0.00125x_1x_3 - 0.00875x_2x_3 - 0.02522\, x_1^2 - 0.02169x_2^2 - 0.0164\, x_3^2$$

$$y_5 = 4.343117648 + 0.14113x_1 + 0.095453x_2 + 0.041578x_3 - 0.15x_1x_2 + 0.05x_1x_3 - 0.025x_2x_3 - 0.00927x_1^2 + 0.114212x_2^2 - 0.062187584x_3^2$$

The adequacy of the obtained mathematical regression models was evaluated using the Fischer $\boldsymbol{Fp}$ criterion. Table 3 lists the calculated $\boldsymbol{Fp}$ values. Thus, considering that $\boldsymbol{Fp} < \boldsymbol{Ftabl}$, the model of technological efficiency of the process can be considered adequate with a 96% confidence probability.

Analysis of the presented graphs shows that, on a three-dimensional model, there are optimal ranges for extrusion temperature (°C), raw material moisture content (%), and screw speed (rpm) at which the physicochemical characteristics of the extruded product are ideal. Figures 2 to 6 show the dependency graphs.

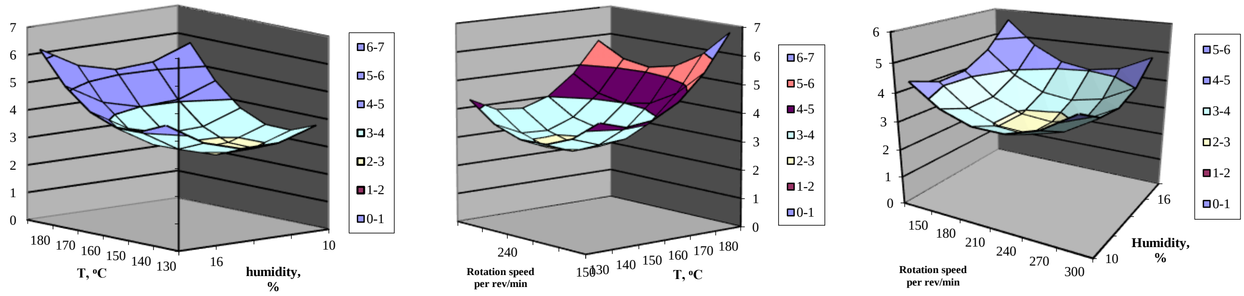

Figure 2. Effect of extrusion parameters on expansion coefficient

The ER values ranged from 2.5 to 6. The maximum value was reached under the following conditions: 170°C, 18% moisture content, and a screw speed of 180 rpm. The coefficient of expansion increases with increasing temperature because the starch gelatinisation and moisture evaporation are enhanced. A high moisture content helps maintain the plasticity of the mass, contributing to a more uniform expansion.

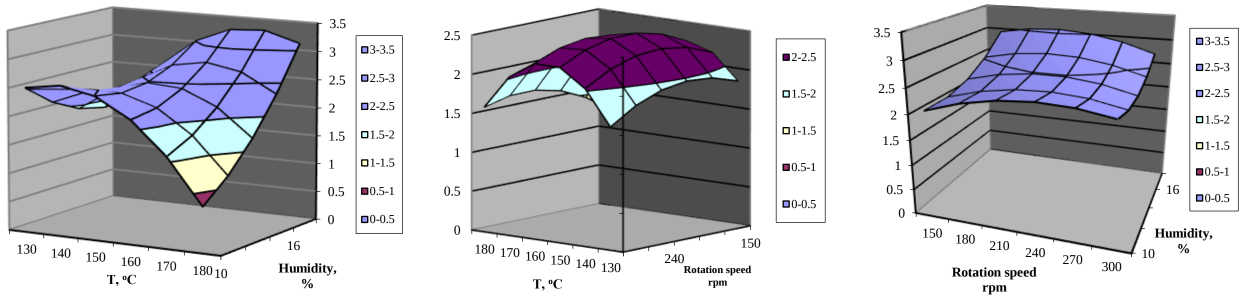

Figure 3. Effect of extrusion parameters on water absorption index

The WAI values ranged from 1.2 to 3.2. The maximum value (3.2) was observed at 170°C, 18% moisture content, and a screw speed of 210 rpm. High WAI values are associated with increased porosity, which boosts the water retention ability of the product. A medium screw speed and high temperature contribute to the formation of a structure with more open pores.

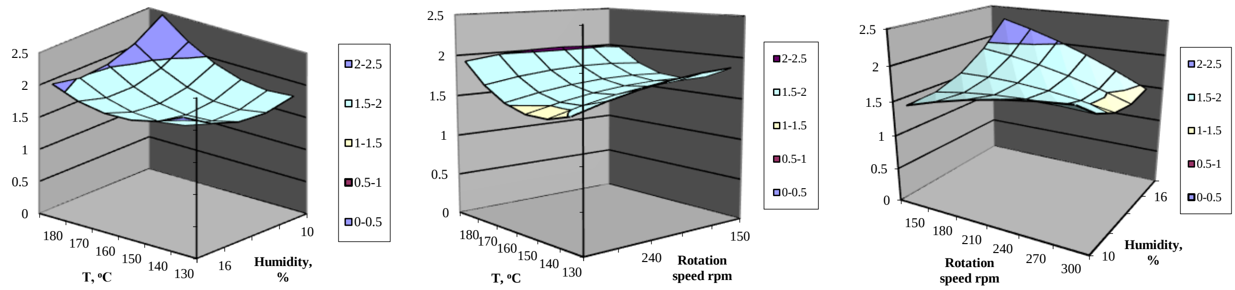

Figure 4. Effect of extrusion parameters on water solubility index

The WSI values ranged from 1.5 to 2.2. An increase in the temperature and screw speed promotes the destruction of starch granules and the release of soluble carbohydrates, enhancing the solubility of the product. Meanwhile, the average humidity level maintains the stability of the structure.

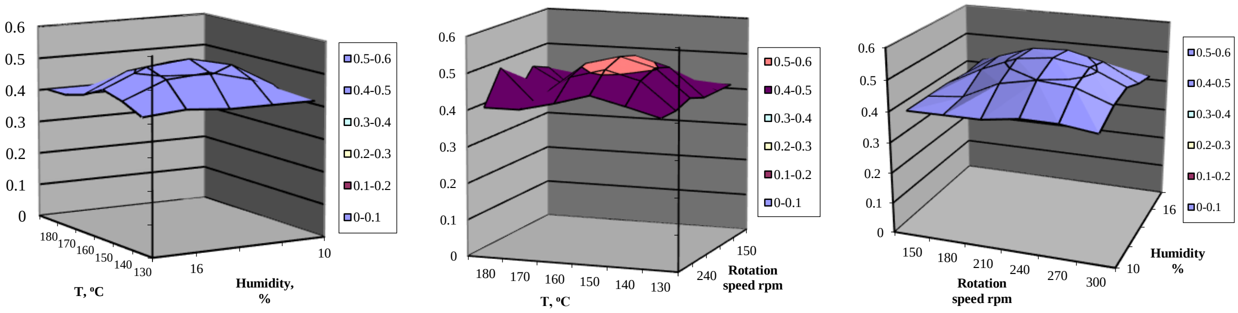

Figure 5. Effect of extrusion parameters on bulk density

The BD values ranged from 0.43 to 0.50 g/cm^3. The minimum value (0.43 g/cm^3) was reached under the following conditions: 170°C, 18% moisture content, and a screw speed of 210 rpm. The density of the product decreases at low humidity and temperature because of the lower moisture content, which could limit expansion. Furthermore, high temperatures and moderate screw speeds contribute to the formation of a light and airy product structure.

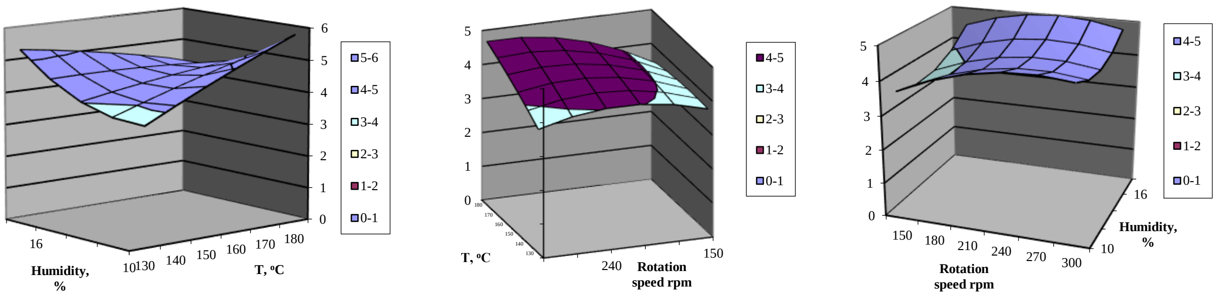

Figure 6. Effect of extrusion parameters on β-carotene content

The β-carotene values ranged from 3.5 to 5.9 mg/100 g. The maximum value was achieved at: 170°C, 18% moisture content and a screw speed of 180–210 rpm.

4. Discussion

The optimal physicochemical properties of the extruded product were achieved at 170°C, 18% humidity and a screw speed of 180–210 rpm. These parameters produced:

- The maximum expansion coefficient, which makes the flakes light and crispy.
- High water absorption, which improves the texture when liquid is added.
- Good solubility in water, which is important for quick product preparation.
- Moderate density, which affects the organoleptic properties and ease of use [23, 24].

Combining corn, rice and pumpkin flour under the given extrusion conditions yielded a product with high organoleptic characteristics. However, the proposed parameters must be adapted, depending on the composition of the raw materials, because a change in the ratio of ingredients can affect the behaviour of the mixture during extrusion.

In extrusion, the key parameters that determine the quality of the product are the temperature, raw material humidity and screw speed. They are closely interrelated, and changing one parameter requires adjusting the others to maintain stable product characteristics [25, 26].

1. Extrusion temperature and raw material humidity:

Temperature and humidity strongly affect starch gelatinisation, protein denaturation and mass texturing.

- Increasing the temperature accelerates gelatinisation and structure formation, but with insufficient humidity (below 12%), it leads to excessive moisture evaporation, texture deterioration, and increased flake fragility.
- With increased humidity (18%–20%), the extrusion temperature should be lowered (160–170°C) to prevent the liquefaction of the mass and degradation of nutrients, especially β-carotene [27, 28].
- The optimal balance is achieved at 170°C and 18% humidity when starch gelatinisation occurs uniformly, and the flake structure remains stable.

2. Extrusion temperature and screw speed

The extrusion temperature also affects the consistency and thermal stability of the product.

- High temperature (over 180°C) combined with low screw speed (less than 150 rpm) increases the residence time of the mass in the high-temperature zone. This can lead to overheating, caramelisation of carbohydrates and loss of β-carotene.
- When the temperature increases, the screw speed (up to 210–230 rpm) must be increased to reduce the residence time of the mixture in the high-temperature zone and avoid the destruction of useful substances [29, 30].
- At 170°C and a screw speed of 180–210 rpm, sufficient mixing is ensured, overheating is prevented, and the mass remains plastic and expands uniformly.

3. Raw material moisture content and screw speed

The raw material moisture content determines the viscosity of the mass and its behaviour during the extrusion process.

- High humidity (18%–20%) makes the raw material more plastic, reduces viscosity and facilitates movement through the extruder. The screw speed can be increased (up to 210–230 rpm) to prevent excessive moisture accumulation [31, 32].
- At low humidity (10%–12%), the mixture becomes more viscous, increasing friction and heat generation. In this case, the screw speed should be reduced to 150–180 rpm to avoid the mechanical destruction of the flake structure.
- The optimal balance between humidity and screw speed is achieved at 18% and 180–210 rpm, when a stable structure and sufficient homogenisation of the mass are ensured.

The best characteristics of the extruded product (maximum expansion coefficient, balanced texture, preservation of β-carotene) are achieved under the following parameters:

- Temperature: 170°C
- Humidity: 18%
- Screw speed: 180–210 rpm

These conditions ensure:

- Sufficient expansion due to moderate temperature and high humidity.
- Stable structure due to controlled screw speed.
- Minimal loss of nutrients, including β-carotene, due to reduced thermal exposure time.

Thus, adjusting one parameter requires proportional adjustment of the others to achieve the desired extruded product. Additional optimisation is required for each new composition, but the proposed parameters are recommended for the industrial production of combined dry breakfasts with added pumpkin flour.

During the extrusion process, partial destruction of the cell walls occurs, which can improve the solubility and digestibility of dietary fibre. High temperature and mechanical action can decrease the insoluble dietary fibre content but increase the proportion of soluble fibre, which positively affects digestion [33, 34]. In this case, the degree of change in the fibre structure depends on the process parameters: temperature, humidity and mechanical action. Studies show that at a moderate temperature (up to 160° C), changes in dietary fibre are minimal, but at a higher temperature (170° C and above), hemicellulose and pectin begin to decompose, which can reduce their functional properties. β-carotene is susceptible to thermal degradation, especially at temperatures above 160°C. It is sensitive to oxygen and light; high temperatures and mechanical stress can accelerate its degradation. However, moderate temperatures (160–170°C), high humidity (16%–18%) and medium screw speed (180–210 rpm) can help reduce β-carotene loss, creating conditions for its stabilisation in the product. An important role is played by the protective effect of the antioxidants contained in pumpkin flour (e.g. vitamin E and phenolic compounds), which can be partially destroyed at high temperatures. However, some studies [35, 36] have indicated increased antioxidant activity after extrusion due to the release of bound phenolic compounds from cellular structures. Thus, the optimal selection of extrusion parameters allows not only minimising antioxidant loss but also improving their bioavailability. To minimise the loss of β-carotene and antioxidants, the following methods can be used:

- Higher raw material moisture (16%–18%) to protect heat-sensitive compounds;
- Adjusting the screw speed (180–210 rpm) to reduce the thermal processing time;
- Adding additional sources of antioxidants (e.g. vitamin C or polyphenols) to stabilise β-carotene.

Extrusion results in some nutrient losses, especially heat-sensitive β-carotene, but proper selection of process parameters can minimise these losses. Optimum conditions (temperature 170°C, humidity 18%, speed 180–210 rpm) help preserve dietary fibre and reduce β-carotene degradation, which makes pumpkin flour a valuable functional ingredient of breakfast cereals. Adding pumpkin flour to extruded breakfast cereals significantly improves their nutritional profile, increasing the fibre, β-carotene and antioxidant contents. This slows down the absorption of carbohydrates, reduces the glycaemic index, and prolongs the feeling of satiety, making the product useful for weight control and maintaining stable blood sugar levels. Thus, pumpkin flour increases not only the nutritional value but also the functionality of breakfast cereals, making them more useful for a wider range of consumers, including people with metabolic disorders.

This study showed that using pumpkin flour in the extrusion process improves the nutritional value of breakfast cereals by increasing the β-carotene and antioxidant contents. The optimum extrusion parameters (170°C, 18% moisture) provide a good balance between the texture and functional characteristics of the product. In the study by Alefew et al. [22], the replacement of lupin and the addition of pumpkin flour significantly increased the content of protein, crude fibre, ash, fat, β-carotene, iron and zinc in an extruded snack made of white rice, lupin and pumpkin, while the total carbohydrate content decreased. Sensory evaluation showed that a certain amount of lupin flour can be added without affecting the taste of the product. Similar results have been obtained in the study by Alefew et al. [22] and Filli [37]. In addition, our data are consistent with the findings of Yağcı et al. [38] and Altan et al. [39], according to which extrusion under controlled conditions improved the WAI and solubility. This is especially important for improving the technological characteristics of the final product, allowing for an optimal combination of crispy texture, rapid swelling in liquid and structure retention during storage. Thus, the obtained data confirm the promise of pumpkin flour for the production of functional flakes, providing high nutritional value and improved organoleptic properties. Importantly, further research should study the interaction of pumpkin flour with other functional ingredients, such as plant proteins or prebiotics, to create even healthier and more heat-resistant products.

5. Conclusion

Optimising the process parameters of the extrusion process in the production of combined dry breakfasts with the addition of pumpkin flour made it possible to establish conditions that ensure the production of products with high physicochemical and organoleptic characteristics. Experimental studies showed that the most significant factors affecting the quality of extrudates are the extrusion temperature, raw material moisture content and screw speed. The optimal parameters – temperature of 170°C, moisture content of 18% and screw speed of 180–210 rpm – contribute to the formation of a porous structure and provide a high expansion coefficient, optimal water absorption, solubility in water, and low bulk density. Adding pumpkin flour to the extrudates significantly increases their nutritional value due to increased dietary fibre, β-carotene and antioxidants. However, adding more than 15% pumpkin flour decreases the expansion coefficient and increases the bulk density due to changes in the moisture content and viscosity of the mixture. Thus, when developing recipes, it is necessary to determine the optimal amount of pumpkin flour to preserve the quality characteristics of the product. The results of the study confirm the prospects of using pumpkin to produce functional foods that meet modern requirements for nutritional value and health benefits. The data obtained can help create new recipes for extruded products with improved organoleptic and nutritional properties. Further research in this area can be aimed at the effects of other plant additives and multicomponent grain mixtures on the technological parameters of extrusion, expanding the range of functional products with high biological value.

6. Declarations

6.1. Author Contributions

Conceptualisation, M.S. and N.A.; methodology, A.S.; software, A.K.; validation, A.D. and M.Y.; formal analysis, M.Y.; investigation, N.A.; resources, A.K.; data curation, N.Ak.; writing—original draft preparation, M.S.; writing—review and editing, M.S.; visualisation, M.S.; supervision, M.S.; project administration, A.S.; funding acquisition, A.D. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

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6.5. Institutional Review Board Statement

Not applicable.

6.6. Informed Consent Statement

Not applicable.

6.7. Declaration of Competing Interest

The authors declare that there are no conflicts of interest concerning the publication of this manuscript. Furthermore, all ethical considerations, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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