

# Porosity and hardness of corn extrudates using dry tomato pomace

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**Abstract:** The incorporation of fiber-rich non-starchy wastes from various industries, into ready-to-eat extrudates, changes their structure and therefore affects their physical properties. The study explored the impact of varying levels of tomato pomace (ranging from 0% to 20%), moisture content in the mixture (ranging from 14.5% to 21.4% on a wet basis), and screw speed (ranging from 156 to 224 rpm) on the hardness of corn extrudates, as well as on parameters such as the number of pores, pore area, average pore size, and pore circularity. It was observed that, the inclusion of tomato pomace increases the hardness of the extrudates by decreasing the average pore size. On the other hand, the average pore size increases, and the hardness decreases with the increase of the screw speed. It was also observed that the higher initial moisture content of the mixtures increases the hardness and results in a more porous structure in the extruded products. The results show that the amount of tomato pomace and the process parameters significantly influence the structure of the extrudates.

## 1 Introduction

In various canning industries, fruits and vegetables are processed into juices, sauces, ketchups, etc. and byproducts known as pomace are generated. These products are mainly used for animal feed, which is low in value. However, this pomace contains valuable nutrients, thus incorporating it into different foods could increase their nutritional value and reduce waste [1].

Extrusion is a process for producing foods that vary in shape, type and texture. Starch-rich raw materials are liquefied due to the high temperature and pressure. The gases trapped in the liquid phase, suddenly expand as they leave the extruder, and as a result the molten mass solidifies to form a porous structure. The high temperature and short impact time preserve their nutritional value (significant nutrient retention) [2].

Cereal extrudates are used for food, but are mainly rich in starch [3], by-products from different industries can enrich extrudates with valuable health substances, but their consumer properties (consumer acceptance) depend on physical characteristics such as hardness and porosity [4].

Most pomace is abundant in fiber, which consists of inert particles. The inclusion of these fibers in extrudates has a significant impact on their structural characteristics. Numerous studies have explored extrudates enhanced with high-fiber pomace products, including sugar beet fibers [5], pectin combined with

wheat fibers [6], cauliflower [7], rice grit in combination with fruit pomace [8], as well as apple, beetroot, carrot, and cranberry [9]. Additionally, apple pomace [10], dehydrated broccoli, and olive paste [11], along with carrot pomace [12], have been investigated in this context.

Fibers have a greater capacity to bind with water and subsequently more water can evaporate from them [5]. The inert particles in pomaces affect the structure by creating more nucleation centres to form pores, leading to a finer network of smaller cells [13].

Insoluble fibers reduce expansion and increase the extrudate density. This makes the structure more difficult to break, i.e., more rigid. Coarse fiber prevents gas bubbles from expanding because the bubbles rupture before reaching their maximum volume [14].

Filamentous particles are assumed to incorporate into the starch matrix and rupture it, whereas particles with rounded edges and irregular shape (apple pomace) do not rupture the starch matrix [15].

Tomatoes are one of the most widely grown vegetables. During processing, a by-product (tomato pomace) is released. It consists of peels, seeds and residual pulp, hence its chemical composition is highly variable [16]. Tomato pomace is rich in fiber, protein and fat [16-18]. The main amount of lycopene and polyphenols is concentrated in the peels [19]. The chemical composition of tomato pomace varies depending on the ratio of peels, seed and pulp and the composition of the starting materials [20].

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The incorporation of tomato pomace products into extrudates has been investigated in various studies: corn, wheat and rice, with tomato skin or paste [21]; corn and tomato pomace [22], sweet potato flour and tomato pomace [23]; barley grist and tomato pomace [1, 24].

The hardness increases with increase of the tomato pomace quantity in the barley– tomato mixture, whereas increasing the screw speed decreases the hardness [1]. The addition of tomato peel alone, increased the hardness of the extrudates [21]. In sweet potato extrudate and dry tomato pomace, increasing the tomato pomace results in increased hardness, in addition higher moisture content decreases expansion and increases hardness [23]. The addition of fiber to corn extrudates strongly reduces their porosity (cell size decreases and cell number increases), resulting in harder products [6, 25].

Most studies typically establish a relationship between expansion and hardness rather than exploring the influence of porosity (including factors such as pore size, pore number, and pore area) on hardness. Additionally, both hardness and porosity are contingent upon the chemical composition of the ingredients and specific process parameters, such as the moisture content of the mixture and the screw speed of the extruder. Conducting research on the incorporation of tomato pomace into extrudates can enhance our understanding of how various parameters interact in the process. Therefore, this study aims to investigate the impact of tomato pomace quantity at varying moisture levels in the mixture and different screw speeds on the porosity and hardness of corn extrudates. Furthermore, it seeks to elucidate the relationship between porosity and the mechanical properties of extrudates, particularly their hardness.

## 2 Materials and methods

### 2.1 Materials

Corn meal from the company "Oberon - X" Ltd. was used (Ravno pole, municipality. "Oberon - X" LTD, Ravno pole Village, Elin Pelin Municipality, Bulgaria), purchased from the commercial network.

Tomato pomace is supplied by Bulcons Parvomay Ltd (Parvomai, Bulgaria) and is dried naturally without direct sunlight. It is ground in a multistage pin mill (VEB Mühlenbau Nossen, Germany) with intermediate sieving on a 500 µm sieve. Fractions above 500 µm are milled again. This is repeated until the residue above 500 µm is less than 0.5% of the initial quantity of the sample. The tomato pomace flour is sealed in polythene bags and stored at 5°C.

### 2.2 Methods

#### 2.2.1 Planned experiment

The influence of the factors was evaluated using a rotatable central composite design (CCD) of 3 factors at 5 levels. The levels of the independent variables are shown in Table 1, and the overall planned experiment is shown in Table 2.

**Table 1.** Levels of variation of independent variables in the central composite design (CCD)

Independent variables	Code	Coded levels of variation				
		-1.682	-1	0	1	1.682
Tomato pomace, %	x <sub>1</sub>	0	4	10	16	20
Screw speed, rpm	x <sub>2</sub>	156	170	190	210	224
Moisture content, % w.b.	x <sub>3</sub>	14.5	16	18	20	21.4

The independent variables are as follows: (x<sub>1</sub>) is the amount of tomato pomace added; (x<sub>2</sub>) is the extruder screw speed; and (x<sub>3</sub>) is the initial moisture content (w.b.) of the mixture. The range of their variation was determined by preliminary trials.

Response surface modelling (RSM) analysis was applied to the experimental data, and second- order regression models were used for modelling, with the following coded values:

$$y = b_0 + b_{11}.X_{12} + b_{22}.X_{22} + b_{33}.X_{32} + b_{12}.X_{1.X2} + b_{13}.X_{1.X3} + b_{23}.X_{2.X3} + b_{111}.X_{12} + b_{222}.X_{22} + b_{333}.X_{32}$$

Where: y are the response variables; x<sub>ij</sub> are the independent variables; b<sub>ij</sub> are the regression coefficients.

#### 2.2.2 Preparation of the mixtures for extrusion

The corn meal and the tomato pomace flour were mixed in a spiral mixer (Moulinex Prepline mixer HM4131, France) for 5 min. The total mass of the mixture was 1000g. The required moisture content was achieved by gradually spraying a pre-calculated amount of distilled water during mixing. The initial moisture content of the meal and tomato pomace was determined by drying at 105°C to constant weight (AOAC, 2005) and the moisture content is the average of three parallel tests.

The moistened mixtures were placed in polyethylene bags and stored at 5°C for 12 h to allow complete moisture equilibration throughout the volume. Before extrusion, the samples were tempered for 2 h at room temperature.

#### 2.2.3 Extrusion

The extrusion was performed using a Brabender 20DN single screw extruder (Brabender GmbH & Co KG, Germany). The extruder consists of 3 zones with independent temperature control. The first zone is the filling zone and the extruded mixture is fed into it via a vertical filling (dosing) screw. The mixture flow rate was regulated by the feed screw speed. It was maintained at 30 min<sup>-1</sup> for all samples and was determined by preliminary experiments. The extrusion was carried out using a 4 mm die; a screw compression ratio of 3:1 and temperatures in

the first, second and third zones, 120, 140 and 170°C, respectively.

**Table 2.** Designed experiment with coded and actual values of independent variables

№	Coded levels			Actual levels		
	Tomato pomace, x <sub>1</sub> , %	Screw speed, x <sub>2</sub> ,rpm	Moisture, x <sub>3</sub> , %w.b.	Tomato pomace, x <sub>1</sub> , %	Screw speed, x <sub>2</sub> ,rpm	Moisture, x <sub>3</sub> , %w.b.
1	-1	-1	-1	4	170	16
2	1	-1	-1	16	170	16
3	-1	1	-1	4	210	16
4	1	1	-1	16	210	16
5	-1	-1	1	4	170	20
6	1	-1	1	16	170	20
7	-1	1	1	4	210	20
8	1	1	1	16	210	20
9	-1.682	0	0	0	190	18
10	1.682	0	0	20	190	18
11	0	-1.682	0	10	156	18
12	0	1.682	0	10	224	18
13	0	0	-1.682	10	190	14.6
14	0	0	1.682	10	190	21.4
15	0	0	0	10	190	18
16	0	0	0	10	190	18
17	0	0	0	10	190	18
18	0	0	0	10	190	18
19	0	0	0	10	190	18
20	0	0	0	10	190	18

#### 2.2.4 Chemical composition

The ash content was determined according to ISO 2171:2007(en) Cereals, pulses and by-products Determination of ash yield by incineration. Total fats are defined by AOAC 945.16, 2000 Distillers Grains and Other Agricultural Materials.

Total sugars were determined titrimetrically after their prior hydrolysis to monosaccharides using concentrated HCl [26]. The resulting monosaccharide residues reacted with Fehling solutions and reduced Cu(II) to Cu(I). To the unreacted amount of Cu(II), after preacidification with sulfuric acid, potassium iodide solution was added in excess. The liberated iodine is titrated with a standard solution of sodium thiosulphate in the presence of starch as an indicator.

Total protein was determined by the Kjeldahl method ISO 20483, Cereals and pulses - Determination of the nitrogen content and calculation of crude protein content.

Total polyphenols were determined by the FolinCiocalteu method [27]. 5 g of pre-homogenized samples (extrudates) were extracted with 100 cm<sup>3</sup> acidified with 2% HCl methanol (95:5) at room temperature for 60 min and filtered. To 0.2 cm<sup>3</sup> of the extracts was added 1.5 cm<sup>3</sup> pre-diluted 1:10 Folin-Ciocalteu reagent. After 5 min, 1.5 cm<sup>3</sup> of Na<sub>2</sub> CO<sub>3</sub> solution (60g/L) was added. The samples were placed in the dark for 90 min, after which the absorbance at 725 nm was measured. A standard straight gallic acid (3,4,5-trihydroxybenzoic acid) was also prepared and the results expressed as mg gallic acid equivalents per 100 g extrudate.

DPPH antioxidant activity was determined by modifying a method described by Kivrak et al. [28]. A 0.15 cm<sup>3</sup> methanolic extract and a 2.85 cm<sup>3</sup> solution of DPPH (2,2-diphenyl-1-picrylhydrazyl) at a concentration of 0.1 mM were incubated in the dark for 15 min at 37°C. Absorbance reduction was read spectrophotometrically at 517nm. Results are expressed as mM Trolox equivalents per gram of raw material based on a previously constructed standard straight line.

#### 2.2.5 Extraction of carotenoids from tomato skins using an organic solvent

A spectrophotometric method was used to determine the total carotenoids, lycopene and β-carotene [29]. 1 g sample was extracted with 10 ml acetone for 30 min at 25°C with stirring (400 rpm). The extract was filtered through a paper filter (MN 640 de). The filtrate was concentrated in a vacuum evaporator at 35°C to 1 ml and the adsorption at 448 and 472 nm was read with a spectrophotometer (Thermo Fisher Scientific, Madison, WI, USA). The amount of total carotenoids, lycopene and β-carotene were determined based on a previously constructed standard table.

#### 2.2.6 Hardness

The hardness of the extrudates was measured with a TA.XT Plus Texture Analyzer (Stable Micro Systems Ltd., England) using a 50 kg load cell and a 2-bladed Kramer shear cell (Pre-test speed 1 mm/s; Test speed 1mm/s; Post-test speed 10 mm/s; Strain 90%). The force-time curve was analyzed by determining the value of the maximum peak of the curve (H, N), which represents the resistance exerted by the extrusion when penetrating the probe and characterizes the hardness of the sample.

#### 2.2.7 Porosity

The porosity of the extrudates was determined by image analysis of the extrudate sections using a modified methodology described by [7]. Samples of extrudates approximately 50 mm in length were cut with a scalpel, longitudinally along the maximum diameter, and photographed with a Pentax Optio M60 camera (Pentax Co., China) at 10MP resolution. The images were converted to 8 bit greyscale. A rectangular field

17.4x4.2mm was examined from the centre of each sample. The pores were separated from the background using the "Niblack" (Auto local threshold) method [30]. The number of pores, pore area (expressed as a percentage of the total surface area), average pore size and circularity were determined. The results are the average values of three parallel measurements. Circularity is expressed as:  $Circularity = (4 \cdot \pi \cdot \text{Pore area}) / (\text{Pore perimeter})^2$ . A value of 1.0 indicates a perfect circle, and when the value approaches 0, it indicates an increasingly elongated pore shape. All image processing and microstructure analyses were performed using the Fiji distribution of ImageJ [31, 32].

### 2.2.8 Statistical processing

Statistical analyses were conducted using the "R: A language and environment for statistical computing" [33]. Experiment planning and analysis were performed using the RemdrPlugin.Doe library [34] run in Rcommander [35]. The coefficients in the RSM models are given in coded form. Student's t-test was used to assess the significance of the coefficients in the models. All analyses were performed using three to six replications.

## 3 Results

### 3.1 Chemical composition of the ingredients

The basic chemical compositions of corn meal and tomato pomace are shown in Table 3. The ash content of both products is similar and no significant change is expected during extrusion. The fat and protein content of tomato pomace is higher than that of corn meal, whereas the carbohydrate content is lower. The amount of fat is 4.87 times higher than that of corn meal. The lower carbohydrate content of the tomato pomace is probably a result of the higher content of insoluble fiber, which is absent from corn semolina.

**Table 3.** Basic chemical composition (dry matter basis) of corn meal and tomato pomace used for extrusion.

Chemical composition	Corn semolina	Tomato pomace
Ash content, %	1.038±0.108	1.009±0.06
Fats, %	1.387±0.246	6.757±0.385
Carbohydrates, %	89.698±1.888	59.368±0.253
Proteins, %	11.107±0.214	17.313±0.302
Total carotenoids, mg/100g	1.3167±0.0569	3.6567±0.0451
Lycopene, mg/100g	0.5267±0.1756	1.1033±0.0378
β-carotene, mg/100g	0.7001±0.120	2.2967±0.0513
Polyphenols, mgGAE/100 g	81.052±1.295	201.612±5.601
DPPH, mM Trolox eq/g	1.673±0.530	2.297±0.341

\*Results are means ± SD of 3 replications

The biologically active substances in the starting materials are listed in Table 3. The tomato pomace outperformed corn meal in all the studied constituents.

The total carotenoids and, in particular, the amount of β-carotene are approximately three times higher than those in corn meal. The amount of lycopene was approximately twofold higher, and the values found in the present study were significantly lower than the values reported in the literature, ranging from 41.37 mg/100 g (c.i.) reported by [17] to 300 mg/100 g (c.i.) reported by [16]. This significant difference can probably be explained by the natural method of drying in which, according to [36, 37], significant amounts of lycopene are lost.

### 3.2 Porosity

Table 4 shows the regression coefficients of the response surface models. The rotational frequency of the extrusion screw and the initial moisture content of the mixtures had a significant linear influence on all the response variables.

The amount of tomato pomace had a significant linear influence only on the average pore size, but a quadratic influence on the same parameter was found for the number of pores. No interaction influence on porosity was observed. The coefficients of determination are close and above 0.7 and the probabilities in the Lackof-fit test are greater than 0.05 and the models are adequate. The exception is circularity where the Lack-offit test is less than 0.05 and the model does not describe the experimental results well.

The number of pores per unit area ranged from 58 to 115, with the lowest number at the highest screw speed and highest moisture (Fig. 1). The number of pores increases with moisture content, this increase being more pronounced at high screw speeds than at low screw speeds. The percentage ratio of "pores: total surface area" varies within a narrow range and ranges from 42.33 to 49.69% (Fig. 2).

The moisture content of the starting mixtures has the strongest positive effect, whereas the screw speed has a stronger positive effect at low moisture contents. Increasing the screw speed and the moisture content of the mixtures results in an increase in the average pore size and, hence, a decrease in the number of pores. As the pores become larger, the areas around them decrease and the porous surface, relative to the background, increases.

The average pore size decreased significantly as the percentage of tomato pomace increased from 0 to 14% (Fig. 3). The decrease in pore size resulted in an increased number of cells per unit area and decreased total pore area.

The pore size is smaller and the number of cells and total area are higher.

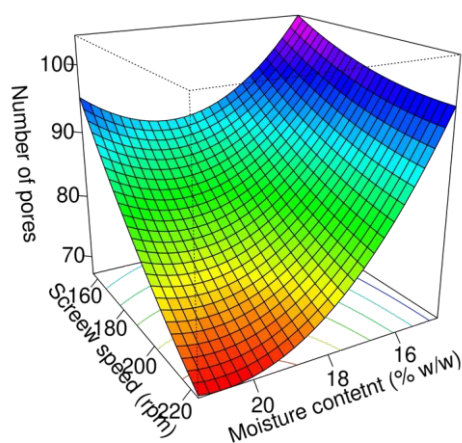
Most studies have found a decrease in porosity with increasing fiber content. The result is a more compact structure with more and smaller cells. Our study confirms the results of Yanniotis et al [6], who added wheat bran to corn extrudates and found that cell size decreased and cell number increased. Similar results were obtained using cauliflower extrudates [7].

The average pore size increases and the number of pores decreases with an increase in pomace over 14%. This can be explained by the rupture of the walls between individual cells and the formation of agglomerates of connected cells.

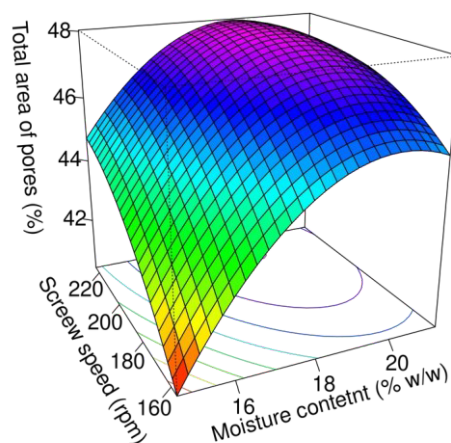
**Table 4.** Results of the regression analysis of microstructure and hardness.<sup>1</sup>

Regression coefficients	Number of pores	Pore area, %	Average pore size, mm <sup>2</sup>	Circularity	Hardness, N
b <sub>0</sub> (constant)	77.33123***	47.14977	0.4438199***	0.70844***	28.8119***
b <sub>1</sub> (linear)	3.75433	-0.26586	-0.0297550*	-0.00991	1.6999**
b <sub>2</sub> (linear)	-5.11894*	0.86595*	0.0366914**	0.00124	-1.8669**
b <sub>3</sub> (linear)	-5.80786*	1.07318**	0.0341483*	0.01459*	3.4248***
b <sub>12</sub> (link)	-0.87500	-0.39150	-0.0011250	-0.00200	0.6488
b <sub>13</sub> (link)	-3.87500	-0.17775	0.0196250	0.00100	0.1013
b <sub>23</sub> (link)	-1.87500	-0.26025	0.0121250	-0.00525	0.3513
b <sub>11</sub> (quadratic)	-6.09738*	0.12765	0.0404344**	-0.00048	0.0156
b <sub>22</sub> (quadratic)	0.62014	-0.28353	-0.0058811	0.00199	-0.7852
b <sub>33</sub> (quadratic)	3.27179	-0.72918*	-0.0133057	-0.00048	1.3644*
R <sub>2</sub>	0.777	0.7491	0.6693	0.6414	0.705
Lack-of-fit	0.192	0.075	0.061	<0.001	0.0675

<sup>1</sup> Figures followed by \*, \*\*, and \*\*\* are statistically significant at P=0.1, 0.05, and 0.01, respectively



**Fig. 1.** Response surface plot for the number of pores as a function of screw speed and moisture content at 10% tomato pomace level



**Fig. 2.** Response surface plot for the total area of pores in % as a function of screw speed and moisture content at 10% tomato pomace level

This is confirmed by the decrease in circularity at higher pomace levels (Table 5).

Similar results were observed with the addition of carrot pomace. Low levels of insoluble fibers (carrot pomace) allow their good distribution, strengthen the starch matrix and allows to improve the structure, as fibers play an active role rather than being an inert material [12]. Carrot pomace in high amounts leads to the rupture of the pore structure [12].

The pore size increases with the screw speed. The extruder pressure is higher at high screw speeds. The rapid decrease in pressure after the die creates more water vapor,

which results in more expansion and larger pore sizes [11].

Pore size increases as moisture content increases. These results are in agreement with the works of other researchers [8]. They showed that the porosity increases as the moisture content increases from 12% to 18% and decreases after 18%. The observed results for the pore size contradict the studies of some authors. They considered that moisture rise had a negative impact on starch gelatinization and reduced extrudate porosity [11, 12].

One possible explanation is the method of wetting the mixture. In this case, the mixture was moistened and aged before extrusion. This allows a uniform moisture

distribution in the material and a more homogeneous movement of water vapour in the pores [10]. Another explanation is the type of additive. Different pomace products adsorb water differently.

The circularity of the pores ranges from 0.672 to 0.769, which means that the shape of the pores is generally irregular, but closer to oval. The only significant positive linear influence on circularity is the moisture content of the mixture.

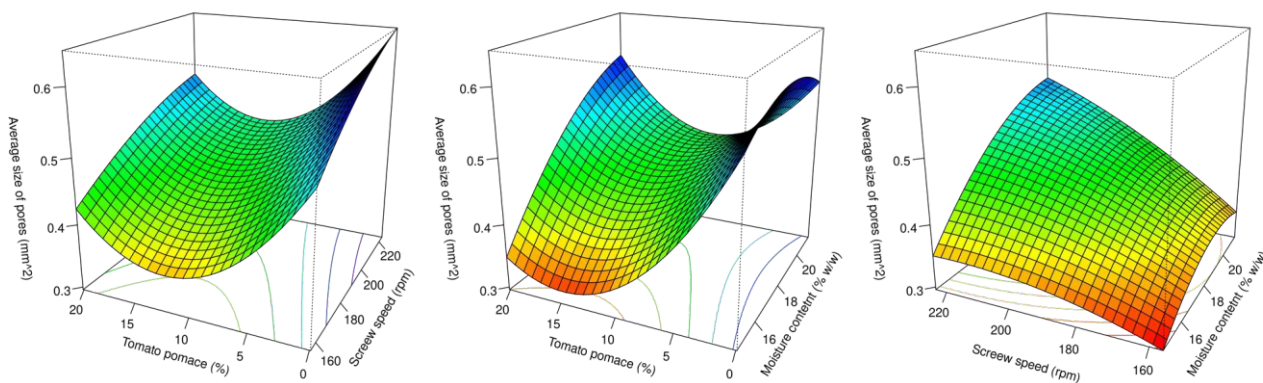
### 3.3 Hardness

The coefficients of the regression equation for hardness are given in Table 4. The mathematical model describes the results with high accuracy ( $R^2 = 0.93$ ). The amount of tomato pomace, screw speed and moisture content of the mixtures have a significant linear influence on hardness. Moisture also has a significant quadratic influence.

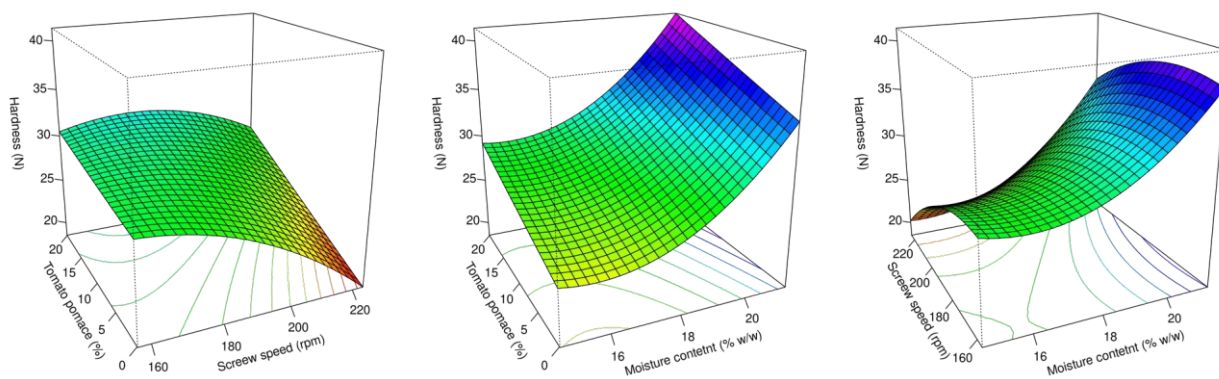
Increasing the tomato pomace from 0 to 20% increases the hardness by 19% (Fig.4). Increasing the tomato pomace content in starch-extruded snacks increases their hardness

[14, 21, 24], which was also observed in our study. The increase in tomato pomace decreased the average pore size and denser structure of the extrudates. This is confirmed by the moderately strong negative correlation between average pore size and hardness (Table 5). The dietary fibers contained in the extrusions probably cause premature rupture of the air "bubbles", which reduces the overall expansion, resulting in a denser product with a less porous structure [6, 38]. The increased amount of non-fibrous ingredients reduces the starch that melts in the extruder, thereby reducing expansion and increasing hardness [21].

The hardness of the extrudates increases with moisture content. The moisture content of the material has been found to have a significant effect on the texture, hardness and crispness of the extruded products [39, 40]. The moisture content of the starting mixture plays a key role in the generation of vapour bubbles in the molten mass as it exits the die [41]. In general, moisture decreases the viscosity of the liquefied mass, therefore, the pressure at the die decreases with increasing moisture content, resulting in a more solid products [40, 42].



**Fig. 3.** Response surface plots for the average size of pores as a function of tomato pomace quantity, screw speed and moisture content



**Fig. 4.** Response surface plots for the hardness of extrudates as a function of tomato pomace quantity, screw speed and moisture content

**Table 5.** Person's correlation coefficients between response variables<sup>1</sup>

	Average size	Circularity	Count	Hardness	%Area
Average size	1	0.1241	-0.9694***	-0.3607*	0.7002***
Circularity		1	-0.0302	0.2798	0.2989
Count			1	0.2972	-0.6677***
Hardness				1	-0.2822
%Area					1

<sup>1</sup>Coefficients followed by \*, \*\*, \*\*\* are statistically significant at P=0.1, P=0.05, P=0.01, respectively

An important factor determining the hardness of the extruded products is the screw speed [40]. Increasing the speed results in greater expansion [11]. This reduces the hardness of the extrudates [1, 25]. This study confirms these results. Increasing the screw speed reduces the hardness by approximately 30%, with the reduction being strongest at screw speeds above 180 rpm.

Hardness correlates negatively with average pore size (Table 5). In this case, the average pore size decreased with increasing tomato pomace, which explains the higher hardness.

## 4 Conclusion

The results obtained in this study show the influence of the amount of tomato pomace and process parameters on the ability to produce extrudates with certain consumer properties. The tomato pomace reduces the porosity of the extrudates, with the average pore size decreasing and their hardness increasing, but it does not significantly affect the number of pores or their total surface area. The porosity of the extrudates is determined by the speed of the extruding screw and the moisture content of the starting mixtures. As these factors increase, the structure of the extrudates changes towards a more 'open' one, with fewer but larger pores. The hardness of the extrudates decreased with increasing the screw speed and increased with increasing the initial moisture content of the mixture. The increase in the hardness of the extrudates and the decrease in their porosity were expected results, and they confirm the results obtained by other authors adding fiber-rich pomace products to extrudates. However, this study will help develop technologies to produce extrudates with higher nutritional value and acceptable consumer properties.

## Dedication

We dedicate this scientific publication to the memory of our friend and colleague Prof. Tsvetko Prokopov, PhD. We miss you!

## References

1. A. Altan, K. L. McCarthy, and M. Maskan, *J. Food Eng.* **84**, 231 (2008)
2. B. Singh, C. Sharma, S. Sharma, In (2017), pp. 1-46
3. A. Cortez and C. Wild-Altamirano, *Nutr. Improv. Maize INCAP Pub.* **L 4**, 99 (1972)
4. H. S. Hegazy, A. E. A. El-Bedawey, E. H. Rahma, and A. M. Gaafar, *Am. J. Food Sci. Nutr. Res.* **4**, 59 (2017)
5. S. Lue, H. E. Huff. *Cereal Chem. USA* (1991)
6. S. Yanniotis, A. Petraki, and E. Soumpasi, *J. Food Eng.* **80**, 594 (2007)
7. V. Stojceska, P. Ainsworth, A. Plunkett, E. Ibanoglu, Ş. İbanoğlu, *J. Food Eng.* **87**, 554 (2008)
8. S. Yağcı and F. Göğüş, *J. Food Eng.* **86**, 122 (2008)
9. V. Stojceska, P. Ainsworth, A. Plunkett, Ş. İbanoğlu, *Food Chem.* **121**, 156 (2010)
10. E. L. Karkle, L. Keller, H. Dogan, S. Alavi, *J. Food Eng.* **108**, 171 (2012)
11. G.I. Bisharat, V.P. Oikonomopoulou, N.M. Panagiotou, M.K. Krokida, Z.B. Maroulis, *Food Res. Int.* **53**, 1 (2013)
12. N. Kaisangsri, R. J. Kowalski, I. Wijesekara, O. Kerdchoechuen, N. Laohakunjit, G.M. Ganjyal, *LWT - Food Sci. Technol.* **68**, 391 (2016)
13. R. Miller, S. Mulvaney, in *Breakf. Cereals They Are Made Second Ed.* (American Association of Cereal Chemists, 2000), p. 562
14. F. Robin, H. P. Schuchmann, S. Palzer, *Trends Food Sci. Technol.* **28**, 23 (2012)
15. M. Masli, B.-J. Gu, B. Rasco, G. Ganjyal, *J. Food Sci.* **83**, (2018)
16. M.D.C. Travieso, T. de Evan, C.N. Marcos, E. Molina-Alcaide, in *Tomato Process. - Prod.*, (Academic Press, 2022), pp. 33-76

17. G. Liadakis, T. Kekes, G. Frakolaki, V. Giannou, C. Tzia, in *Tomato Process. - Prod.* (Academic Press, 2022), pp. 117-148
18. Z. Lu, J. Wang, R. Gao, F. Ye, G. Zhao, *Trends Food Sci. Technol.* **86**, 172 (2019)
19. S. M. Choudhari, L. Ananthanarayan, *Food Chem.* **102**, 77 (2007)
20. Y. Silva, B. Borba, V. Pereira, M. Reis, M. Caliari, M. Brooks, T. Ferreira, *Int. J. Food Sci. Nutr.* **70**, 1 (2018)
21. Z. Dehghan-Shoar, A.K. Hardacre, C.S. Brennan, *Food Chem.* **123**, 1117 (2010)
22. A. Jabeen, H. Naik, N. Jan, S. Z. Hussain, T. Amin, A. Rafiq, *Br. Food J.* **124**, 3705 (2021)
23. P. Dhungana, *Afr. J. Food Sci.* **8**, 264 (2014)
24. M. Okba, E. Abdelrasoul, M. Gomaa, *J. Food Dairy Sci.* **5**, 139 (2014)
25. H. Chanvrier, E. Jakubczyk, E. Gondek, J.-C. Gummy, *Innov. Food Sci. Emerg. Technol.* **24**, 61 (2014)
26. N. Schoorl, A. Regenbogen, *Z. Für Anal. Chem.* **56**, 191 (1917)
27. R. M. Lamuela-Raventós, *Meas. Antioxid. Act. Capacity* (John Wiley & Sons, Ltd, 2018), pp. 107-115
28. İ. Kivrak, M. E. Duru, M. Öztürk, N. Mercan, M. Harmandar, G. Topçu, *Food Chem.* **116**, 470 (2009)
29. M. Chalukova, H. Manuelyan, in *Genet. Improv. Tomato*, (Springer, Berlin, Heidelberg, 1991), pp. 179-195
30. W. Niblack, *An Introduction to Image Processing* (Prentice Hall, Englewood Cliffs, 1986)
31. J. Schindelin, I. Arganda-Carreras, E. Frise, V. Kaynig, M. Longair, T. Pietzsch, S. Preibisch, C. Rueden, S. Saalfeld, B. Schmid, J.-Y. Tinevez, D.J. White, V. Hartenstein, K. Eliceiri, P. Tomancak, A. Cardona, *Nat. Methods* **9**, 676 (2012)
32. C.A. Schneider, W.S. Rasband, K.W. Eliseiri, *Nat. Methods* **9**, 671 (2012)
33. R.C. Team. *A language and environment for statistical computing. R Foundation for Statistical Computing.* (2013)
34. U. Groempung, *Tutorial for Designing Experiments Using the R Package RcmdrPlugin.DoE*, Department II (Beuth University of Applied Sciences Berlin, 2011)
35. J. Fox, M. Bouchet-Valat, *Rcmdr: R Commander* (2021)
36. B. J. Allison, C. W. Simmons, *Biomass Bioenergy.* **105**, 331 (2017)
37. J. Shi, M. Le Maguer, *Crit. Rev. Biotechnol.* **20**, 293 (2000)
38. P. Ainsworth, Ş. İbanoğlu, A. Plunkett, E. İbanoğlu, V. Stojceska, *J. Food Eng.* **81**, 702 (2007)
39. S. Chakraborty, D. Singh, B. Kumbhar, S. Chakraborty, *Food Bioprod. Process. - Food Bioprod Process.* **89**, 492 (2011)
40. X. Meng, D. Threinen, M. Hansen, D. Driedger, *Food Res. Int.* **43**, 650 (2010)
41. J.L. Kokini, C.N. Chang, L.S. Lai, *Food Ext. Sci. Technol.* **740**, 631 (1992)
42. Y. Liu, F. Hsieh, H. Heymann, H.E. Huff, *J. Food Sci.* **65**, 1253 (2000)