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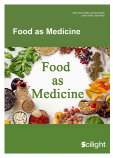

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Process Optimization and Product Characterization of Tomato Pomace Incorporated Biofunctionalized Extruded Puffs: Effect of Extruder Operational Parameters

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How To Cite: Kumar, A.; Arora, B.; Joshi, A.; et al. Process Optimization and Product Characterization of Tomato Pomace Incorporated Biofunctionalized Extruded Puffs: Effect of Extruder Operational Parameters. *Food as Medicine* **2026**, *2*(3), 8. https://doi.org/10.53941/fm.2026.100008

Received: 10 March 2026
Revised: 22 July 2026
Accepted: 22 July 2026
Published: 14 August 2026

Abstract: The effects of tomato pomace concentration, feed moisture, and screw speed on physicochemical and biofunctional attributes of tomato pomace-corn based extrudates was investigated. As tomato pomace concentration increased, expansion ratio and porosity of the extrudates decreased resulting in harder products. This effect of increased hardness, was mitigated by correspondingly increasing the moisture content. With increasing moisture content, porosity first increased and extrudate structure enhanced as shown by mean pore size but with further increase collapse of the extrudate immediately after exiting the extruder was observed. Screw speed positively impacted the crispness and the structure of the extrudate contributing to enhanced sensory properties moderating the impact of pomace addition. The formulation comprising of 14.39% tomato pomace concentration at a screw speed of 213 rpm and feed moisture of 13.44% was optimized and validated. The tomato pomace functionalized puffs had a higher protein (10.6%) and dietary fiber (15.19%) content compared to control (1.58% and 9.97%, respectively) as well as lycopene content of 0.54 mg/100 g. This process allows for inclusion fiber rich tomato pomace as a functional ingredient in corn based puffed extruded snack which are a healthier option than currently available extruded snack options.

Keywords: extrusion; tomato pomace; lycopene; structural analysis; textural analysis

1. Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated vegetable crops belonging to the Solanaceae family and is native to the Andean region [1]. Tomatoes are extensively grown for both fresh consumption and processing. They are a source of substantial amounts of vitamins, fiber, sugars, and essential minerals, all of which contribute to health benefits. As per the estimates of FAO 2020 [2], the worldwide area and production of tomatoes has reached 5.05 million hectares and 186.82 million metric tons, respectively. Tomato ranks third in area (8.53 lakh ha) and production (213.23 lakh metric tons) among vegetables in India [3]. The two main seasons for growing and processing tomatoes are Kharif (August to October) and Rabi (December to April). They can also be cultivated in the off-season (May to July) under protected conditions, yielding lower quantities but of higher quality. Tomatoes are highly perishable and must be sold quickly after harvest, often at very low prices, if not processed. Processing of tomatoes is an excellent alternative, as it ensures better prices for farmers and provides consumers with diverse tomato products year-round. Tomato is recognized as a key vegetable for export by APEDA (Agricultural and Processed Food Products Export Development Authority). It can be used for the development of different processed items like puree, paste, whole peeled tomatoes, diced products, juice, sauces, soups, etc. Processed tomato products, especially puree and paste, are in high demand for export because they can be stored for long period and can be reconstituted and reformulated into other tomato products whenever needed.

Since tomatoes are seasonal, only some are used for fresh consumption while the majority are processed into paste, juice, and other forms. During tomato processing, a by-product i.e., tomato pomace, is generated. On an average, tomato pomace accounts for approximately 13–15% (w/w) of the raw material [4]. In light of this, it is estimated that the global yield of tomato pomace is between 5.4 and 9.0×10^6 metric tonnes, annually. For this reason, using or disposing of tomato pomace is a crucial issue that cannot be ignored by the food sector.

Tomato pomace consists mainly of peel and seeds with fiber as the major component (25.4–50.0% on dry matter basis). Total protein in the pomace ranges from 15.4 to 23.7%, while total fat and mineral content vary from 5.4 to 20.5% and 4.4 to 6.8%, respectively. A major problem faced by the food industry is the accumulation, handling, and disposal of processing waste. For this reason, the proposal of the recovery of food wastes is rapidly expanding around the world, with an increasing demand for their transformation into useful by-products that help the environmental balance.

Tomato pomace powder is a favorable ingredient for extrusion owing to its high fibre content. Extrusion cooking is classified as a high temperature/short time process to produce fiber-rich products [5,6]. In the extruder, the food mix is thermomechanically cooked to high temperature, pressure and shear stress which are generated in the screw-barrel assembly. The cooked melt is then texturized and shaped in the die [7]. During extrusion, the fibre content remains intact, making the final product a good source of fiber.

Although a high temperature process, extrusion can be optimized to ensure retention of maximum nutritional value and bioactives of the feed ingredients. Along with flavor, major antioxidants and color compounds of tomato i.e., lycopene are thermostable. Therefore, high temperature exposure for short time as during extrusion process does not impair the biofunctionality of the tomato pomace. Moreover, the tomato pomace adds natural color and flavor to the extruded products, enhancing their appeal without the need for synthetic additives [8]. Inclusion of pomace in extruded products promotes sustainability by utilizing waste from tomato processing alongside contributing to environmental conservation.

As a complex multivariate process, extrusion requires careful control if product quality is to be maintained. Changes in the product quality during extrusion primarily depends on the raw material properties (composition and moisture content) and the extruder conditions such as barrel temperature, screw speed and feed moisture [9]. Any change in feed composition, influenced by the type of ingredients, as well as the amount of each ingredient, and any process variable that affects physical or chemical transformation of macromolecules during extrusion can influence extrusion performance and quality of the extrudate [10]. The objective of this study was to elucidate the effect of incorporation of foam mat dried tomato pomace powder on physicochemical, structural and sensory properties of corn extrudates. Further, the extrusion parameters for the development of tomato pomace powder fortified puffed snacks were optimized to achieve a functional snack product with consumer acceptable sensory quality.

2. Materials and Methods

2.1. Procurement of Tomato and Making of Pomace Powder

Ripe tomatoes of the processable variety 'Pusa Prasanskrit' released by ICAR-Indian Agricultural Research Institute, New Delhi were harvested from the field. Pomace was collected after juice extraction and subjected to foam mat drying to achieve uniformity and better retention of bioactives. Foam-mat drying is highly superior for processing tomato pomace because it significantly accelerates moisture removal by incorporating a foaming agent that expands the surface area, drastically shortening drying times. This rapid, low-to-moderate temperature thermal processing effectively prevents the severe degradation of heat-sensitive, high-value bioactives like lycopene and polyphenols.

2.2. Extrusion Process

Feed formulation comprising tomato pomace powder and corn were blended using a ribbon blender. A CRD design (3 × 3 × 3) was used with feed moisture (12–16%), screw speed (200–300 rpm) and tomato pomace concentration (5–15%) as independent variables. Moisture was added into the formulation as per experiment design (varying from 12–16%). The conditioned feed was extruded using a twin screw extruder (Bharat Technologies Pvt Ltd., West Bengal, India) fitted with a circular die of 5 mm diameter, at different screw speeds (200, 250 and 300 rpm) at a die extrusion temperature of 160 °C.

2.3. Physical Attributes of Extruded Snack

2.3.1. Expansion Ratio

The diameter of 10 extrudates per treatment combination was measured using a vernier caliper (Mityoto, Japan). The expansion ratio was calculated as the ratio of average extrudate diameter and the die-diameter. Only the extrusion treatments which produced extrudates with an expansion ratio greater than 1.8 are reported here (Table 1), since extrudates with an expansion ratio of less than 1.8 were invariably dense and hard.

2.3.2. Porosity

The porosity of the extrudates was determined by powdering the samples and calculating by using the relationship between the tapped and particle densities of the powder [11].

$$\text{Porosity} = \left(1 - \frac{\rho_b}{\rho_{tap}}\right)$$

where, ρ_{tap} is tapped density, ρ_b is bulk density

2.3.3. Texture Analysis

The textural attributes of extruded product were determined by using Stable Micro Texture analyzer (model: TA + Di, Stable Micro System, Surrey, UK) with SS flat cylindrical probe (0.25S) in compression mode to determine the hardness of developed products. TA settings for hardness were: Pre-test speed 1 mm s^{-1}, test speed 0.5 mm s^{-1}, post-test speed 10 mm s^{-1}. As compression proceeded fracture could be observed as a series of peaks on force-time curve. The number of major peaks was considered as an indication of 'crispiness'. Ten replicates per sample were tested for all textural parameters.

2.3.4. Mean Pore Size

Digital scans of extrudate cross section were taken by using a scanner (Epson Perfection V370 Flatbed Photo Scanner, Byatarayanapura, Bangalore, India). The scanned image was used to examine the cellular microstructure of extrudates and to quantify the average cell size and wall thickness using image processing software Image J (Version 1.x, National Institutes of Health, Bethesda, MD, USA). The mean pore size was expressed as a mean of diameter of 50 cells.

2.3.5. Color

Colour of developed extruded snacks was measured using Hunter Lab Lab Scan XE. (Hunter Associates Laboratory, Reston, VA, USA) and expressed as L* (Lightness/darkness), a* (redness/greenness) and b* (yellowness/blueness) values.

2.4. Proximate Composition and Lycopene Content

The developed extruded snacks were evaluated for carbohydrate, fat, fibre and ash [12].

Lycopene content in the developed tomato pomace incorporated extruded snacks was estimated as per [13] using solvent phase distribution principle using acetone and petroleum ether solvent. Absorbance of ether fraction was recorded at 502 nm on a spectrophotometer for lycopene content quantification.

$$\text{Lycopene (mg/100 g)} = \frac{3.12 \times \text{OD} \times \text{volume made up (ml)} \times 100}{\text{weight of sample (g)} \times 1000}$$

2.4.1. Sensory Evaluation

Prepared puffed snacks were evaluated by a semi-trained panel of 50 members (aged 20–28; 26 males; 24 females) for color & appearance, crispness, taste, flavor and overall acceptability using 9-point hedonic scale with rating 1 as extremely dislike, 5 as neither like nor dislike and 9 as like extremely. The panelists were routine snack consumers and were explained the significance of the trial and sensory descriptors beforehand.

Table 1. Sample nomenclature, extrusion parameters and physicochemical properties of selected tomato pomace-corn puff extrudates. Values are average of three measurements. The superscript alphabets indicate significant difference ($p < 0.05$).

S. No	Extrusion Parameters			Extrudate Properties								
	Tomato Pomace Concentration (%)	Screw Speed (rpm)	Feed Moisture (%)	Expansion Ratio	Porosity	Crispness	Hardness (N)	Overall Acceptability Score (OAA)	a-Value	Mean Pore Size (µm)	Lycopene Content (mg/100 g)
1	10	250	14	2.002 ± 0.21^{a}	0.582 ± 0.08^{b}	9.5 ± 1.0^{a}	59.47 ± 3.43^{c}	9 ± 0.5^{a}	17.99 ± 1.3^{a}	1.19 ± 0.06^{b}	0.527 ± 0.012^{bc}
2	10	250	12	1.903 ± 0.32^{b}	0.599 ± 0.03^{ab}	6 ± 0.5^{c}	54.18 ± 2.78^{d}	9 ± 0.5^{a}	18.59 ± 1.5^{a}	1.09 ± 0.05^{a}	0.156 ± 0.014^{f}
3	5	300	14	1.937 ± 0.14^{b}	0.602 ± 0.06^{ab}	4.5 ± 0.5^{d}	52.14 ± 3.87^{e}	5 ± 1^{d}	16.86 ± 0.9^{b}	1.39 ± 0.07^{bc}	0.749 ± 0.023^{a}
4	10	200	16	1.927 ± 0.15^{b}	0.367 ± 0.04^{e}	7.5 ± 1.0^{b}	79.85 ± 4.12^{a}	7 ± 1^{c}	18.59 ± 0.6^{a}	1.76 ± 0.03^{d}	0.562 ± 0.012^{b}
5	5	250	12	2.053 ± 0.22^{a}	0.580 ± 0.06^{b}	6 ± 0.5^{c}	64.11 ± 3.87^{b}	7 ± 0.5^{c}	16.17 ± 1.2^{b}	1.95 ± 0.04^{e}	0.359 ± 0.009^{d}
6	5	200	14	1.925 ± 0.18^{b}	0.627 ± 0.05^{a}	9 ± 0.5^{a}	80.68 ± 4.26^{a}	7 ± 0.5^{c}	16.22 ± 1.1^{b}	2.43 ± 0.03^{f}	0.203 ± 0.011^{e}
7	10	200	12	2.034 ± 0.26^{a}	0.489 ± 0.06^{cd}	8 ± 0.5^{b}	66.15 ± 2.69^{b}	7 ± 1^{c}	18.66 ± 0.9^{a}	1.98 ± 0.06^{e}	0.577 ± 0.012^{b}
8	5	250	16	2.072 ± 0.16^{a}	0.505 ± 0.07^{c}	7.5 ± 1.0^{b}	53.42 ± 2.19^{de}	8 ± 0.5^{b}	16.19 ± 1.2^{b}	1.92 ± 0.04^{e}	0.125 ± 0.011^{f}

2.4.2. Statistical Analysis

The experiment was planned and carried out using a 3 × 3 × 3 completely randomized design (CRD) with tomato pomace concentration, feed moisture content and screw speed as variables. ANOVA was performed, followed by Tukey's Honest Significant Differences (HSD) test, to determine the statistical significance of the data obtained in the investigation.

3. Results and Discussion

3.1. General Observation on Extrudate Structure

The images of tomato pomace incorporated puffed extruded snacks from all formulation combinations depicted noticeable differences in color ranging from light yellow to dark orange (Figure 1). The internal architecture of the extrudates reveals that some extrudates have a more aerated structure with visible pores, while others appear denser, indicating differences in expansion during extrusion process. As tomato pomace incorporation increased, the product was observed to become dense and dark in color (more orange-red).

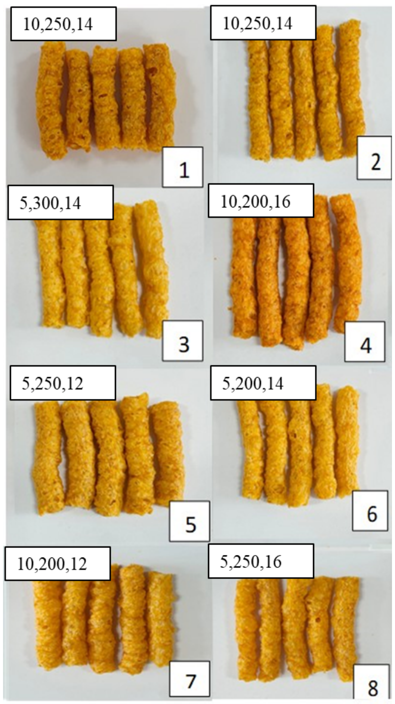


Figure 1. Experimental samples of selected (expansion ratio > 1.8) tomato pomace-corn puff extrudates. Samples are coded from 1 to 8 and the values at the top of each sample represents the operational parameters as tomato pomace concentration (%), screw speed (rpm) and feed moisture content (%), respectively.

3.1.1. Expansion Ratio

The expansion ratio of experimental samples varied from 1.90 to 2.07 (Table 1). The effect of pomace concentration and screw speed has been shown in Figure 2a. The impact of tomato pomace concentration, screw speed, and feed moisture on the expansion ratio was significant. Upon increasing the pomace concentration from 5 to 15% there is a significant decrease in expansion ratio. This decline is likely due to the fiber content in tomato pomace, which disrupts the starch matrix thus, reducing puffing ability. This decrease was found to be linearly related. Effect of pomace concentration and feed moisture is demonstrated in Figure 2b. Similarly, ref. [14] reported that increasing the level of tomato pomace resulted in decrease in expansion ratio of extrudates. This may be attributed to the dilution effect of pomace on starch. Ref. [15] also studied the effect of addition of carrot pomace powder (CPP) and cauliflower trimmings powder (CTP) on bulk density and expansion ratio of extrudates on optimization of the extrusion process for development of high fibre soybean-rice ready-to-eat snacks. They observed a positive relationship between CPP and CTP and bulk density values. Fibre present in CPP and CTP has the capacity to absorb water, which can lead to products with increased density and lower expansion ratio. The effect of increase of feed moisture from 12 to 16% was not statistically significant. During the extrusion process, the high temperature and pressure conditions inside the barrel caused the sample's moisture to superheat.

Subsequently, sudden pressure drops at the die exit led to the evaporation of moisture, resulting in product expansion. Being rich in dietary fibre, tomato pomace also has a notable impact on the expansion of goods that are extruded. As the extrudate comes out of the die, the higher soluble dietary fibre content in tomato pomace combines with the starch molecules to generate a viscoelastic mass that can expand. The moisture level of the feed has a major impact on the radial expansion ratio of extruded products derived from tomato pomace. The molecular structure of amylopectin in the starch-based material can change when the moisture level rises, which can result in decreased melt elasticity and a quadratic influence on radial expansion because it releases stored energy throughout the expansion process and increases the radial expansion ratio, melt elasticity is essential to radial expansion [16]. Higher feed moisture content during extrusion, however, may alter the starch-based material's amylopectin structure, lowering melt elasticity and decreasing radial expansion [17]. Furthermore, longer residence times may weaken the material's amylopectin networks, which would be detrimental to the radial growth. Dough elasticity may further be reduced by the plasticization of the melt brought on by higher feed moisture content, thereby limiting expansion. Additionally, a higher feed moisture level decreases friction in the barrel, screw, and feed material, which hinders starch gelatinization and limits product expansion. Similar to other starch-based polymers, faster screw speeds enable the material to flow through the die more quickly, increasing product expansion [18]. As initial analysis demonstrated that puffs with expansion ratio less than 1.8 were extremely hard, only samples with expansion ratio greater than 1.8 were used for further analysis and optimization.

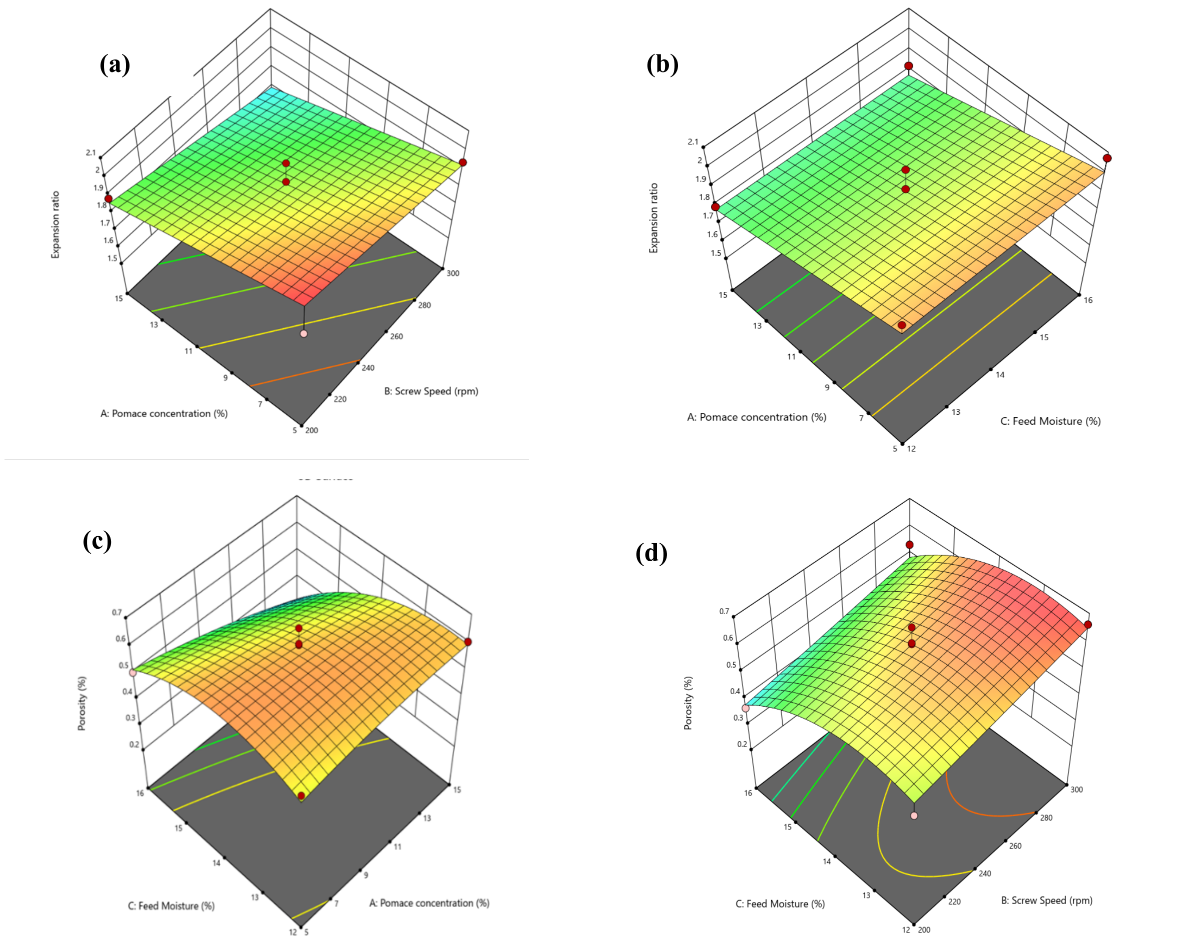


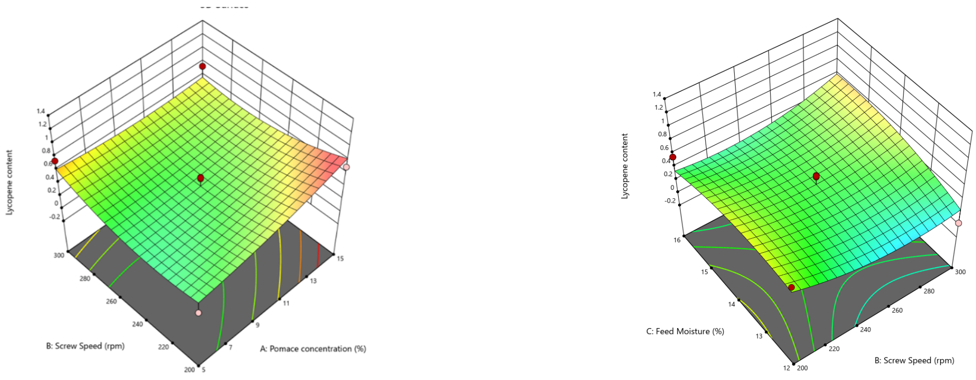
Figure 2. Effect of processing parameters on expansion ratio (**a**,**b**) and porosity (**c**,**d**), of puffed extruded snack (**a**) Effect of screw speed and pomace concentration (**b**) feed moisture and pomace concentration (**c**) Effect of pomace concentration and feed moisture (**d**) screw speed and feed moisture on porosity of puffed extruded snack.

3.1.2. Porosity

The porosity of experimental samples varied from 0.36 to 0.62 (Table 1) from Figure 2c, it was evident that on increasing feed moisture from 12 to 16%, porosity increases significantly from 12 to 14% and thereafter it decreases. Thus, a quadratic effect of feed moisture on porosity was observed. At a feed moisture of 16%, the hydrophilic fiber networks strongly compete with starch for available water, limiting free water for complete starch gelatinization. This restriction increases melt viscosity and reduces melt elasticity, which ultimately suppresses bubble expansion upon exiting the die, explaining the quadratic drop observed in porosity. Impact of tomato pomace concentration, screw speed, and feed moisture on the porosity of the developed extruded puffed snack is shown in Figure 2d. The quadratic effect of feed moisture on porosity can be explained by the interactions between moisture content and the food matrix during processing. Initially, as feed moisture increases from 12% to 16%, porosity increases due to enhanced gelatinization and the expansion of starch granules, leading to a more open structure [19]. Ref. [20] also reported increase in porosity and fine cellular structure with increasing matrix uniformity owing to starch gelatinization and protein viscosity development. However, beyond a certain moisture level (14%), the excess water starts to act as a plasticizer, reducing the viscosity of the mix as reported by [21]. The inelasticity of the melt may contribute to collapse of the structure after exiting the extruder resulting in decreased porosity even with higher number of cells. This can lead to decreased expansion and, subsequently, lower porosity.

3.1.3. Lycopene Content

The lycopene content of experimental samples varied from 0.12 mg/100 g to 0.74 mg/100 g (Table 1). The impact of tomato pomace concentration, screw speed, and feed moisture on the lycopene content of the extruded snacks is shown in Figure 3a,b. As the concentration of pomace increases in the extruded product, there is a linear increase in the lycopene content. Similar trend was also reported by ref. [22] while studying the impact of tomato pomace powder added to extruded snacks on the in vitro gastrointestinal behaviour and stability of bioactive compounds. The increase in lycopene content in extruded products with the rising concentration of pomace can be attributed to several factors. Pomace, particularly from tomatoes or other red fruits and vegetables, is rich in lycopene, a powerful antioxidant which is retained even after juicing or processing of the primary fruit [23]. As the concentration of pomace increased in the extruded product, the total lycopene content also increased proportionally. Further, lycopene is relatively heat-stable compared to other nutrients. The extrusion process, which involves high temperature and pressure, does not significantly degrade lycopene. Thus, the lycopene from pomace is preserved and is available in the extruded product. Another factor maybe that the extrusion process can enhance the binding of lycopene to the food matrix, making it more stable and potentially more bioavailable. The high temperature and shear forces involved in extrusion can break down cell walls and release lycopene, making it more accessible [24]. In summary, the increase in lycopene content with higher pomace concentrations is due to the intrinsic lycopene content in the pomace and the retention and release of this compound during the extrusion process. As the screw speed during extrusion decreased, the lycopene content of the extruded products increased. On the other hand, ref. [25] reported a convex shaped variation in lycopene content to increase in screw speed as indicated by the significant negative effect of a quadratic term of screw speed (X_3^2). It indicates that as screw speed increases, the lycopene content of the extrudates first rises and then falls again. Decrease in lycopene concentration with increased screw speed can be attributed to input of larger quantity of mechanical energy, inducing even mixing and distribution of tomato pomace exposing more lycopene to heat. The increase in lycopene content with the decrease in screw speed during the extrusion process can be explained by several factors. Lower screw speeds typically generate less heat due to reduced friction and shear forces. Lycopene is a heat-sensitive compound, and excessive heat can cause its degradation. By operating at lower screw speeds, the extrusion process maintains a lower temperature, thereby preserving more lycopene. High screw speeds result in higher shear forces, which can mechanically degrade lycopene molecules while reduced screw speed minimizes shear force, leading to less mechanical breakdown of lycopene. Extrusion cooking enhances lycopene stability in tomato pomace by utilizing a High-Temperature Short-Time (HTST) profile, where intense mechanical shear and high pressure rapidly disrupt rigid cell walls to liberate lycopene from its complexed matrix. This ultra-short residence time minimizes the thermal and oxidative degradation typically caused by other prolonged processing methods. Furthermore, the combined heat and shear induce a structural transition from *all-trans* to *cis*-isomers, which are less prone to crystallization and more bioavailable [26]. High screw speeds can increase pressure within the extruder, potentially leading to the breakdown of sensitive compounds like lycopene [27].



(**a**) (**b**)

Figure 3. Effect of processing parameters on lycopene content of puffed extruded snack (**a**) Effect of pomace concentration and screw speed (**b**) screw speed and feed moisture.

3.1.4. Crispness

The crispness of the developed extruded puffed snack increased significantly from 4.5 to 9.5 (Table 1) as the screw speed increased from 200 to 300 rpm (Figure 4a,b). Ref. [28] also found similar results during optimization of the twin-screw extrusion process to produce okara-maize snack foods using response surface methodology. Increase in crispness upon increasing screw speed may be attributed to generation of greater shear force and mechanical energy, which disrupts the cellular structure of the ingredients more effectively. This disruption helps to create a more porous and expanded structure in the final extruded product, leading to increased crispness. The increased screw speed also improves the mixing and uniform distribution of heat and moisture throughout the extruder. This uniformity ensures better gelatinization of starch and protein denaturation, contributing to a more uniform and crisp texture in the final product [29]. Moreover, higher screw speeds typically reduce the residence time of the material within the extruder. This reduction minimises the degradation of sensitive nutrients and components, preserving the desired textural properties and contributing to a crisper product [30].

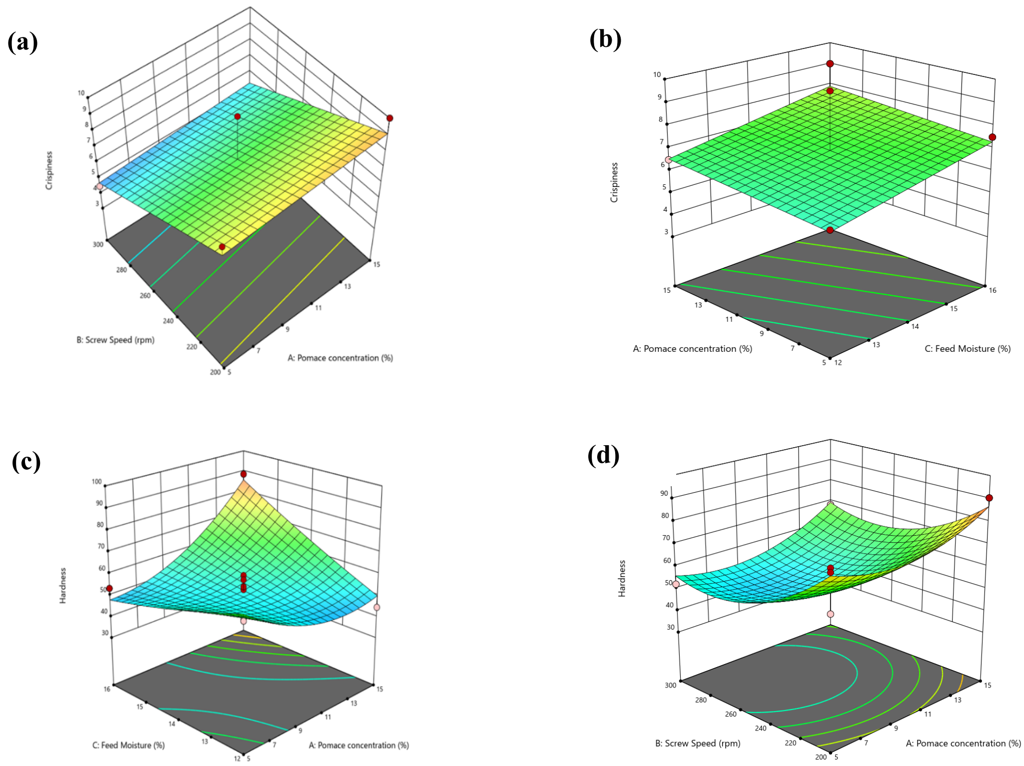


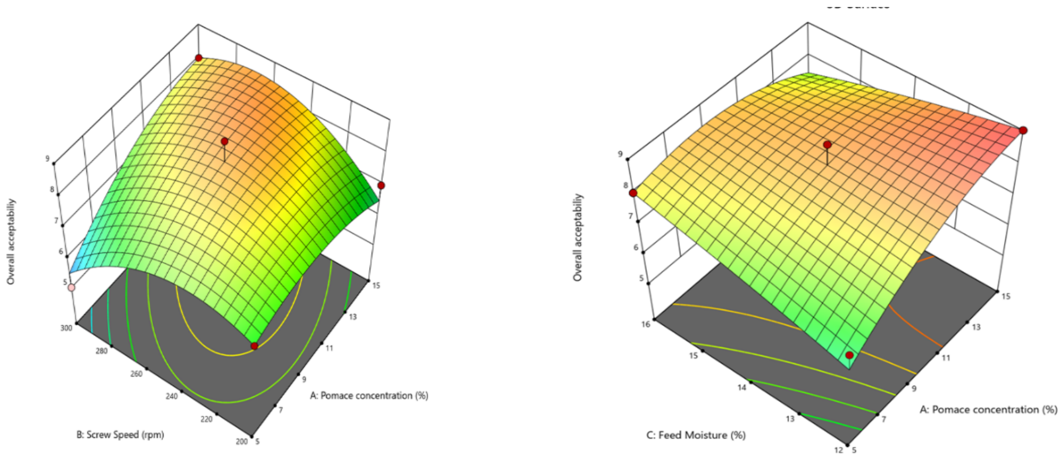
Figure 4. Effect of processing parameters on crispness (**a**,**b**) and hardness (**c**,**d**) of puffed extruded snack (**a**) Effect of pomace concentration and screw speed (**b**) feed moisture and pomace concentration (**c**) Effect of pomace concentration and feed moisture (**d**) pomace concentration and screw speed.

3.1.5. Hardness

The hardness of developed puffed extruded snacks is influenced by factors such as tomato pomace concentration, screw speed, and feed moisture. As the pomace concentration increased from 5 to 15%, hardness increased from 53.42 to 80.68 N as shown in Figure 4c and Table 1. The hardness of extruded products increased as the pomace concentration increased. Ref. [20] also concluded similar results in their research on impact of tomato pomace powder added to extruded snacks on the in vitro gastrointestinal behaviour and stability of bioactive compounds. This effect can be attributed to several factors related to the physical and chemical properties of the pomace. Tomato pomace is rich in dietary fibre, including both soluble and insoluble fibres. These can increase the rigidity and structural integrity of the extruded product, leading to increased hardness. Extrusion cooking often relies on the gelatinization of starch to create a puffed and less dense product. Tomato pomace has a lower starch content compared to typical cereal-based ingredients, reducing the extent of starch gelatinization and thus resulting in a harder product. The natural pectin and other polysaccharides present in tomato pomace can act as binding agents, creating a denser network within the extruded matrix. This increased density contributes to the overall hardness of the product. As the feed moisture concentration increased from 12–16%, there is an increase in hardness value of puffed extruded snacks. Similar results were also found by [15] while working on optimization of the extrusion process for development of high fibre soybean-rice ready-to-eat snacks using carrot pomace and cauliflower trimmings. Previously, ref. [31] had reported that as the feed moisture increased, there is an increase in hardness of cassava (*Manihot esculenta Crantz*) flour extrudates. Higher feed moisture content can lead to more extensive gelatinization of starches during the extrusion process. Gelatinization involves the breaking down of intermolecular bonds in starch molecules in the presence of water and heat, leading to the formation of a gel-like structure. This gel-like structure can contribute to a denser and harder texture in the final product. The starch gel forms a more rigid matrix, which increases the hardness of the extruded snack. Fibre affects cell wall thickness and raises the hardness of the extruded products [32]. Increased moisture content can also enhance the denaturation of proteins. Denatured proteins can interact more extensively, forming stronger networks within the extruded product. These stronger protein networks contribute to the overall hardness of the snack. Higher moisture content can improve the structural integrity of the extruded product by facilitating better cohesion among the components resulting in a more compact and harder product.

3.1.6. Sensory Evaluation

The overall acceptability of extrudates varied from 5 to 9. Figure 5a shows that as the screw speed increased from 200 to 250 rpm, there is an initial but on-significant increase in overall acceptability followed by a decline. Similar result was also reported by [25] wherein a quadratic response on sensory acceptability was observed in extruded products made from tomato pomace incorporation in relation to screw speed. At lower screw speeds, the mixing and cooking of the extrudate may not be optimal, leading to an uneven texture and possible undercooking. As the screw speed increases, the mixing improves, and the heat distribution becomes more uniform, enhancing the overall texture and flavour, which contributes to the initial increase in acceptability. At moderate screw speeds, the shear forces are sufficient to break down the fibrous components of the tomato pomace and facilitate the expansion of the extrudate. This can result in a more desirable, puffed texture that is generally preferred by consumers. At higher screw speeds, the shear forces and temperatures may become too high, leading to over-shear and over-cooking of the product. This can cause degradation of the structural components, resulting in a denser, less desirable texture. Higher screw speeds increase mechanical shear, which alters the expansion ratio and cell structure of the puffs. This directly impacts the mechanical crispness and mouthfeel that are the key drivers of sensory evaluation scores. Additionally, overcooking can lead to the development of off-flavours and burned notes, which negatively affect overall acceptability. Higher screw speeds can also lead to increased moisture loss during extrusion [33] resulting in a drier product, which may not be as palatable [34]. Higher screw speeds can accelerate nutrient degradation, particularly of sensitive compounds like vitamins and antioxidants present in tomato pomace. The loss of these nutrients can affect both the flavour profile and the perceived health benefits of the product, leading to decreased acceptability.



(a) **(b)**

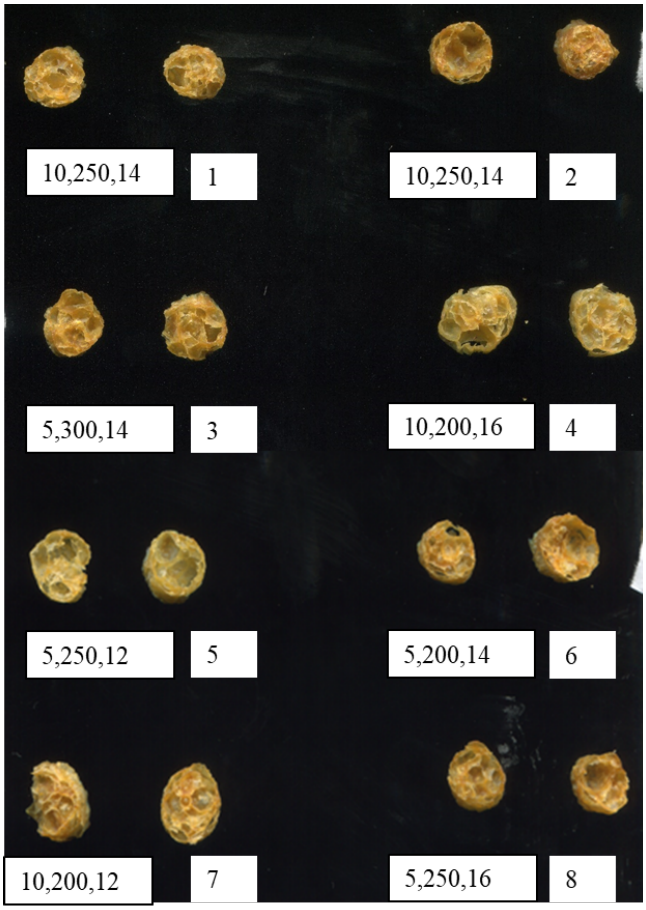
Figure 5. Effect of processing parameters on overall acceptability of puffed extruded snack (**a**) Effect of pomace concentration and screw speed (**b**) pomace concentration and feed moisture.

3.1.7. a-Value

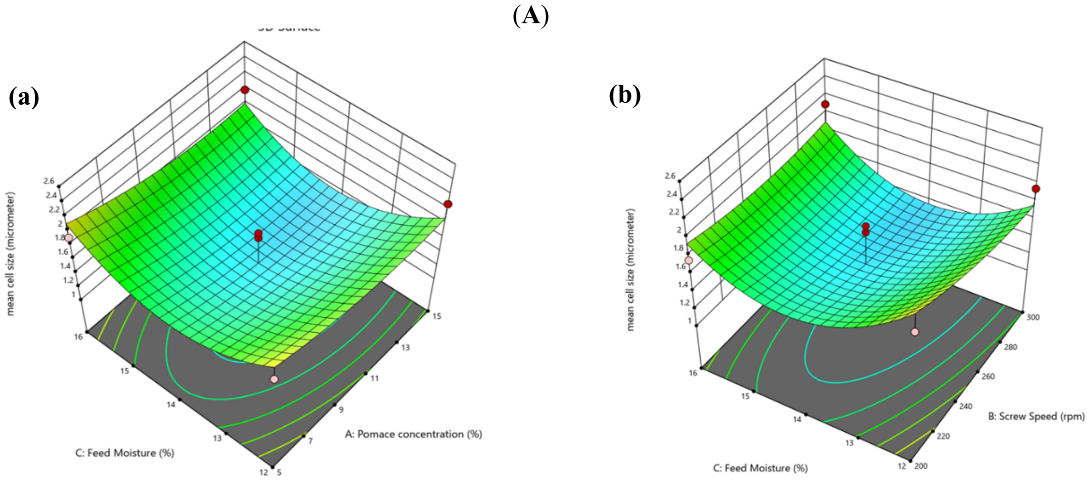
As the pomace concentration increases from 5 to 15, there is significant increase in 'a' value from 15 to 21. The increase in the a-value (redness) of puffed extruded snacks with increasing tomato pomace concentration can be attributed to the natural pigments present in tomato pomace. Tomato pomace is rich in lycopene, a carotenoid pigment responsible for the red colour of tomatoes. As the concentration of tomato pomace increased, the lycopene content in the extruded product also increased, leading to a more intense red colour, reflected by a higher a-value (Table 1). The results are in concurrence with those of [14] in extruded barley-tomato pomace snacks. As the pomace concentration increased there was an increase in a-value and decrease in L-value due to the increase in the lycopene content. As the screw speed increased, a-value decreased most probably owing to increased porosity due to formation of finer air cells. Similar results have been previously reported by [14] in extruded barley-tomato pomace snacks and [35] during extrusion of maize grits. Lycopene and other carotenoids in tomato pomace are relatively heat-stable. During the extrusion process, these pigments are not significantly degraded, allowing the colour to be retained or even enhanced due to the concentration effect, contributing to the increase in redness (a-value). The extrusion process involves high temperatures that can trigger the Maillard reaction between amino acids and reducing sugars, although this effect is minimal. The extrusion process can cause physical and chemical changes that intensify the natural colours of the ingredients. The concentration of tomato pomace increases the availability of natural pigments, leading to a more pronounced red colour in the final product.

3.1.8. Mean Pore Size

The cross-sectional microstructure of the extrudate samples is shown in Figure 6a. The mean pore size of experimental samples varied from 1.09 to 1.98 (Table 1). Figure 6b shows that as the pomace concentration increased from 5 to 15% there is a non-significant increase in mean pore size up to 1.9 µm followed by a decline. The increase in the mean cell size with increasing pomace concentration is due to the incorporation of dietary fibres and other bioactive compounds present in the pomace. These compounds can interact with the food matrix, leading to changes in its microstructure and causing an increase in cell size [36]. However, as the concentration of pomace increased beyond 15%, a decrease in mean cell size was observed due to the excessive number of fibres and other components that start to interfere with the formation of a uniform matrix. High levels of pomace may lead to the aggregation of particles, which may result in a denser structure with smaller cell sizes. Additionally, the high fibre content can absorb more water, which might limit the expansion of cells during processing. With increasing feed moisture content, the mean cell size first decreased and then increased following a quadratic pattern. This can be attributed to the effect of feed moisture on melt viscosity. At low moisture, higher melt viscosity allowed for development of a finer pore structure. With increasing feed moisture content, melt viscosity decreased but the moisture was not enough to plasticize the tomato pomace fibre, resulting in fewer and larger pores. With further increase in moisture, plasticization of tomato pomace fibre resulted in formation of a uniform matrix promoting small cell architecture. Ref. [20] also reported that high viscosity extruder feed results in a finer cell structure owing to enhanced melt elasticity. Previously [37,38] have concluded similar effects of melt viscosity and matrix uniformity on cell size and architecture of corn extrudates.



(**A**)



(**B**)

Figure 6. (**A**) Cross-sectional images of selected (expansion ratio > 1.8) tomato pomace-corn puff extrudates. Samples are coded from 1 to 8 and the values at the top of each sample represents the operational parameters as tomato pomace concentration (%), screw speed (rpm) and feed moisture content (%), respectively. (**B**) Effect of processing parameters on mean pore size of puffed extruded snack (**a**) Effect of pomace concentration and feed moisture (**b**) screw speed and feed moisture.

3.2. Optimized Tomato Pomace Extrudates

The formulation comprising of 14.39% tomato pomace concentration with 213 rpm screw speed and 13.44% feed moisture, was optimized and validated with the values predicted by the model (0.716 desirability). The respective values of dependent variables of predicted v/s actual values were as follows: expansion ratio (1.852 v/s 1.835), crispiness (8.383 v/s 7.826), hardness (70.91 v/s 68.17 N) and overall acceptability scores (7.548 v/s 7.20), porosity (0.515 v/s 0.412), lycopene content (0.667 v/s 0.545), a-value (20.009 v/s 22.004), and mean cell size (1.419 v/s 1.312).

3.3. Proximate Composition

The proximate composition of control (without tomato pomace incorporation) and optimized tomato pomace extrudates is shown in Table 2. The tomato pomace functionalized puffs had a higher protein (10.60 v/s 1.58%) and dietary fiber (15.19 v/s 9.97%) content. Lycopene content of optimized puffs was 0.545 mg/100 g. Thus, a biofunctionalized nutritional snack product was developed in this study.

Table 2. Proximate composition of control and optimized puffed extruded snacks.

Parameter	Control Puffs	Optimized Tomato Pomace Functionalized Puffs	Significance ($p < 0.05$)
Fat (%)	0.85 ± 0.04	1.32 ± 0.06	S
Protein (%)	6.58 ± 0.08	10.60 ± 0.23	S
Ash (%)	1.86 ± 0.03	1.92 ± 0.04	NS
Dietary fiber (%)	9.97 ± 1.46	15.19 ± 0.15	S
Carbohydrates (%)	85.74 ± 1.37	64.41 ± 0.61	S
Overall acceptability score	8.3 ± 0.57	7.00 ± 0.12	S
Crispiness	8.5 ± 0.17	8.2 ± 0.06	NS
Hardness (N)	31.5 ± 5.28	68.37 ± 0.60	S

Values are average of three measurements and are represented as mean ± SD. The significant difference is evaluated by student's *t* test (S: significant, NS: not significant).

4. Conclusions

An optimized formulation comprising 14% foam-mat-dried tomato pomace, an extrusion screw speed of 213 rpm, and a feed moisture of 13.5% was successfully validated, showing high alignment with model predictions (desirability: 0.716). Fundamentally, the high mechanical shear and thermal energy during extrusion disrupted the rigid lignocellulosic fibers of the pomace, allowing for the systematic incorporation of fiber fragments into the starch melt without severely compromising the cell wall extensibility of the expanding matrix. These findings demonstrate that foam-mat-dried tomato pomace can be successfully upcycled from a zero-value agro-industrial waste into a premium, biofunctional additive. The optimized extruded puffs offer the food industry a clean-label, ready-to-eat snacks enriched with natural colorants and dietary antioxidants, bridging the gap between sustainable waste valorization and high-value functional food development. Thus foam mat tomato pomace powder can be successfully used as a biofunctional additive for the development of extruded puffs as a natural source of color and antioxidants. The developed extruded snacks can open new avenues for the utilization of tomato pomace which otherwise treated as a zero-value waste. This research paves the way for the study of the precise starch-fiber-lycopene binding mechanisms and its effect on the bioaccessibility of bioactives in novel functionalized snack products.

Author Contributions

A.K.: Formal analysis, Writing original draft; B.A.: Methodology, Resources, Data analysis, Writing—review and editing. A.J.: Conceptualization, Reviewing, Supervision. S.S.: Resources, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Institutional Review Board Statement

Consent was obtained from all the participants for the sensory evaluation. The panel selection was done after informing the composition of the product and screening the participants for any potential allergencity.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the sensory evaluation.

Data Availability Statement

Data will be made available on reasonable request.

Acknowledgments

The authors acknowledge ICAR-Indian Agricultural Research Institute for providing the research facilities.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

References

1. Tilahun, S.; Choi, H.R.; Baek, M.W.; et al. Antioxidant Properties, γ-Aminobutyric Acid (GABA) Content, and Physicochemical Characteristics of Tomato Cultivars. *Agronomy* **2021**, *11*, 1204. https://doi.org/10.3390/agronomy11061204.
2. FAO. *FAOSTAT Statistical Database*; Food and Agriculture Organization: Rome, Italy, 2020.
3. Ministry of Agriculture & Farmers Welfare (2024). Department of Agriculture & Farmers' Welfare Releases the Third Advance Estimates of 2023–24 of Area and Production of Various Horticultural Crops. Available online: https://www.pib.gov.in/PressReleasePage.aspx?PRID=2057249&reg=48&lang=2 (accessed on 13 August 2026).
4. Zuorro, A.; Fidaleo, M.; Lavecchia, R. Enzyme-Assisted Extraction of Lycopene from Tomato Processing Waste. *Enzyme Microb. Technol.* **2011**, *49*, 567–573. https://doi.org/10.1016/j.enzmictec.2011.04.020.
5. Gaosong, J.; Vasanthan, T. Effect of Extrusion Cooking on the Primary Structure and Water Solubility of β-Glucans from Regular and Waxy Barley. *Cereal Chem.* **2000**, *77*, 396–400. https://doi.org/10.1094/CCHEM.2000.77.3.396.
6. Vasanthan, T.; Gaosong, J.; Yeung, J.; et al. Dietary Fiber Profile of Barley Flour as Affected by Extrusion Cooking. *Food Chem.* **2002**, *77*, 35–40. https://doi.org/10.1016/S0308-8146(01)00318-1.
7. Arhaliass, A.; Bouvier, J.M.; Legrand, J. Melt Growth and Shrinkage at the Exit of the Die in the Extrusion-Cooking Process. *J. Food Eng.* **2003**, *60*, 185–192. https://doi.org/10.1016/S0260-8774(03)00039-4.
8. Eliopoulos, C.; Markou, G.; Langousi, I.; et al. Reintegration of Food Industry By-Products: Potential Applications. *Foods* **2022**, *11*, 3743. https://doi.org/10.3390/foods11223743.
9. Harper, J.M. *Extrusion of Foods*; CRC Press: Boca Raton, FL, USA, 1981; Vol. 2.
10. Alam, M.S.; Kaur, J.; Khaira, H.; et al. Extrusion and Extruded Products: Changes in Quality Attributes as Affected by Extrusion Process Parameters: A Review. *Crit. Rev. Food Sci. Nutr.* **2016**, *56*, 445–473. https://doi.org/10.1080/10408398.2013.779568.
11. Sethi, S.; Joshi, A.; Seth, K.; et al. Phytonutrient content, antioxidant potential and acceptability of muffins functionalized with soy and citrus industry waste. *J. Food Process. Preserv.* **2022,** *46*, e16606. https://doi.org/10.1111/jfpp.16606.
12. AOAC. *Official Methods of Analysis*, 17th ed.; AOAC: Rockville, MD, USA, 2000.
13. Ranganna, S. Handbook of Analysis and Quality Control for Fruit and Vegetable Products; Tata McGraw-Hill: Noida, India, 1986.
14. Altan, A.; McCarthy, K.L.; Maskan, M. Evaluation of Snack Foods from Barley-Tomato Pomace Blends by Extrusion Processing. *J. Food Eng.* **2008**, *84*, 231–242. https://doi.org/10.1016/j.jfoodeng.2007.05.014.
15. Alam, M.S.; Pathania, S.; Sharma, A. Optimization of the Extrusion Process for Development of High Fibre Soybean-Rice Ready-to-Eat Snacks Using Carrot Pomace and Cauliflower Trimmings. *LWT* **2016**, *74*, 135–144. https://doi.org/10.1016/j.lwt.2016.07.031.
16. Alvarez-Martinez, L.; Kondury, K.P.; Harper, J.M. A General Model for Expansion of Extruded Products. *J. Food Sci.* **1988**, *53*, 609–615. https://doi.org/10.1111/j.1365-2621.1988.tb07768.x.
17. Kristiawan, M.; Chaunier, L.; Della Valle, G.; et al. Modeling of Starchy Melts Expansion by Extrusion. *Trends Food Sci. Technol.* **2016**, *48*, 13–26. https://doi.org/10.1016/j.tifs.2015.11.004.
18. Sandrin, R.; Caon, T.; Zibetti, A.W.; et al. Effect of Extrusion Temperature and Screw Speed on Properties of Oat and Rice Flour Extrudates. *J. Sci. Food Agric.* **2018**, *98*, 3427–3436. https://doi.org/10.1002/jsfa.8855.
19. Zambrano, Y.; Contardo, I.; Moreno, M.C.; et al. Effect of Extrusion Temperature and Feed Moisture Content on the Microstructural Properties of Rice-Flour Pellets and Their Impact on the Expanded Product. *Foods* **2022**, *11*, 198. https://doi.org/10.3390/foods11020198.
20. Arora, B.; Schulz, P.; Rizvi, S.S.H. In-process Flow Behavior and Structure Formation during Supercritical Fluid Extrusion of Milk Protein Concentrate. *J. Food Process. Preserv.* **2021**, *45*, e15348. https://doi.org/10.1111/jfpp.15348.

21. Levine, H.; Slade, L. Water as a Plasticizer: Physico-Chemical Aspects of Low-Moisture Polymeric Systems. In *Water Science Reviews*; Cambridge University Press: Cambridge, UK, 1988; Volume 3, pp. 79–185. https://doi.org/10.1017/CBO9780511552083.002.
22. Yagci, S.; Calıskan, R.; Gunes, Z.S.; et al. Impact of Tomato Pomace Powder Added to Extruded Snacks on the In Vitro Gastrointestinal Behaviour and Stability of Bioactive Compounds. *Food Chem.* **2022**, *368*, 130847. https://doi.org/10.1016/j.foodchem.2021.130847.
23. Eslami, E.; Carpentieri, S.; Pataro, G.; et al. A Comprehensive Overview of Tomato Processing By-Product Valorization by Conventional Methods Versus Emerging Technologies. *Foods* **2023**, *12*, 166. https://doi.org/10.3390/foods12010166.
24. Tonyalı, B. Effect of Extrusion on Functional Components in Tomato Pulp Added Extrudates and In Vitro Bioaccessibility of Lycopene. Master's Thesis, Middle East Technical University, Ankara, Turkey, 2014.
25. Dhungana, P.K.; Chauhan, A.; Singh, S. Evaluation of Extrudate from Sweet Potato Flour and Tomato Pomace Blend by Extrusion Processing. *Afr. J. Food Sci.* **2014**, *8*, 264–277. https://doi.org/10.5897/AJFS2013.1074.
26. Rodriguez-Amaya, D.B.; Esquivel, P.; Meléndez-Martínez, A.J. Comprehensive Update on Carotenoid Colorants from Plants and Microalgae: Challenges and Advances from Research Laboratories to Industry. *Foods* **2023**, *12*, 4080. https://doi.org/10.3390/foods12224080.
27. Ruiz-Gutiérrez, M.G.; Sánchez-Madrigal, M.Á.; Quintero-Ramos, A. The Extrusion Cooking Process for the Development of Functional Foods. In *Extrusion of Metals, Polymers and Food Products*; Qamar, S.Z., Ed.; IntechOpen: London, UK, 2018. https://doi.org/10.5772/intechopen.68741.
28. Shi, C.; Wang, L.J.; Wu, M.; et al. Optimization of twin-screw extrusion process to produce okara-maize snack foods using response surface methodology. *Int. J. Food Eng.* **2011**, *7*, 2. https://doi.org/10.2202/1556-3758.1909.
29. Nakamichi, K.; Nakano, T.; Yasuura, H.; et al. The Role of the Kneading Paddle and the Effects of Screw Revolution Speed and Water Content on the Preparation of Solid Dispersions Using a Twin-Screw Extruder. *Int. J. Pharm.* **2002**, *241*, 203–211. https://doi.org/10.1016/S0378-5173(02)00241-1.
30. Gao, J.; Walsh, G.C.; Bigio, D.; et al. Residence-Time Distribution Model for Twin-Screw Extruders. *AIChE J.* **1999**, *45*, 2541–2549. https://doi.org/10.1002/aic.690451210.
31. Badrie, N.; Mellowes, W.A. Effect of Extrusion Variables on Cassava Extrudates. *J. Food Sci.* **1991**, *56*, 1334–1337. https://doi.org/10.1111/j.1365-2621.1991.tb04766.x.
32. Mendonca, S.; Grossmann, M.V.E.; Verhé, R. Corn Bran as a Fibre Source in Expanded Snacks. *LWT* **2000**, *33*, 2–8. https://doi.org/10.1006/fstl.1999.0601.
33. Chevanan, N.; Rosentrater, K.A.; Muthukumarappan, K. Effect of DDGS, Moisture Content, and Screw Speed on Physical Properties of Extrudates in Single-Screw Extrusion. *Cereal Chem.* **2008**, *85*, 132–139. https://doi.org/10.1094/CCHEM-85-2-0132.
34. Karel, M.; Heidelbaugh, N.D. Recent Research and Development in the Field of Low-Moisture and Intermediate-Moisture Foods. *Crit. Rev. Food Sci. Nutr.* **1973**, *3*, 329–373. https://doi.org/10.1080/10408397309527144.
35. Ilo, S.; Liu, Y.; Berghofer, E. Extrusion Cooking of Rice Flour and Amaranth Blends. *LWT* **1999**, *32*, 79–88. https://doi.org/10.1006/fstl.1998.0497.
36. Aguilera, J.M. The Food Matrix: Implications in Processing, Nutrition and Health. *Crit. Rev. Food Sci. Nutr.* **2019**, *59*, 3612–3629. https://doi.org/10.1080/10408398.2018.1502743.
37. Alavi, S.H.; Gogoi, B.K.; Khan, M.; et al. Structural Properties of Protein-Stabilized Starch-Based Supercritical Fluid Extrudates. *Food Res. Int.* **1999**, *32*, 107–118. https://doi.org/10.1016/S0963-9969(99)00062-8.
38. Chen, K.H.; Rizvi, S.S.H. Rheology and Expansion of Starch-Water-CO_2 Mixtures with Controlled Gelatinization by Supercritical Fluid Extrusion. *Int. J. Food Prop.* **2006**, *9*, 863–876. https://doi.org/10.1080/10942910600853823.