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Research article

Fabrication of textured functional ingredient based on apple: Sesame by-product

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ABSTRACT

The search for new sources of fortified components from low-cost and sustainable sources has become a trend in the last decade. Food byproducts containing valuable bioactive compounds such as dietary fiber, protein, and phytochemicals are being used as substrates for obtaining beneficial components that can promote health. Extrusion is an efficient technology for converting food by-products into nutrient-rich food ingredients. The objective of this work was to optimize the extrusion process to obtain the best combination of moisture content (14, 18 and 22%) and screw speed (SS) (120,150 and180 rpm), apple pomace (AP): semi-defatted sesame cake (SDSC) blends (25:75, 50:50 and 75:25 w/w) to fabricate textured functional ingredients (TFI) with high values of expansion ratio (ER), water absorption index (WAI), brightness level, total phenolic compounds (TPC) and antioxidant activity (AA) and lower hardness based on a central composite design. The optimal treatment was determined at 176 rpm SS, 18% moisture content and a ratio of (75:25) AP: SDSC. The desirability value has indicated an appropriate match between the predicted and the observed response. TFI exhibited higher soluble dietary fiber fraction (WAI) values and lower plate count values during 30 days of storage compared to the unprocessed by-product, suggesting that TFI could be successfully used for the manufacture of innovative, high quality products such as porridge, beverages, cookies, soups and others that could provide health benefits based on the values obtained.

1. Introduction

Overweight and obesity have reached epidemic proportions in the last two decades in both developed and developing countries (Jame., 2008 and [1]). This epidemic, due to lifestyle, has led to more attention being paid to fiber-rich products. Dietary fiber as a functional ingredient is used extensively in the food industry [2]. The WHO recommended an average daily intake of 25 g fiber for women and 38 g for men, up to 50 years of age [3].

Agri-food byproducts from fruit and vegetable processing, grain milling, and oil extraction would be one of the accessible and cost-effective sources of dietary fiber (Wang et al., 2015). The presence of other bioactive compounds in wastes such as proteins, phenolic compounds, vitamins, and minerals also shows that they play an important role in promoting health [4,5]. Approximately 35% of the world's food and agricultural products are wasted each year; Global food waste has become a negative impact on the environment due to the problems associated with its accumulation [6]. The generation of huge amounts of waste opens an important area for applied

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research aimed at reducing and managing it efficiently ([7].) In order to create wealth from waste, it must be processed quickly through appropriate technology [7,8]. Extrusion can transform food waste into value-added ingredients [9]. Extrusion technology applies high temperatures and high pressure simultaneously in a short time (HTST), resulting in unique product shapes, a reduction in microbial load and the activity of harmful enzymes, and increasing the amount of soluble fiber and digestibility [10,11]. The functionalization of apple pomace by extrusion has been investigated in only a few studies [12,13].

Apple pomace (AP) is extruded as a minor ingredient in starchy matrices to increase the fiber and bioactivity content of extruded products, such as breakfast cereals and snacks [11,14]. Shmid et al. (2021) showed that extrusion affected the functionality of apple pomace, improving the water absorption index (WAI) and water solubility index (WSI) and increasing the soluble fiber fraction. Nascimento et al. [15], Carvalho et al. [16], and Huang et al. [17] concluded that, using semi defatted sesame cake (SDSC) up to 20% is a valuable alternative to improve the functional, nutritional and sensory properties of corn extrudates. Ruiz-Armenta et al. [18] optimized extrusion conditions to produce SDSC with maximum WAI, total phenolic content, and antioxidant activity. No paper has been published on a composite blend of textured AP: SDSC [19,20]. The aim of this study was to determine the optimum condition of AP: SDSC ratio, screw speed rotation, feed moisture content to obtained extruded ingredient.

2. Materials and methods

2.1. Materials

Dried AP with 5.8 ± 0.11% moisture (db), 6.48 ± 0.31 % proteins (db), 2.5 ± 0.64% fat (db), 3.3 ± 0.31 % ash (db), Carbohydrate 39.1 ± 2.1% (db) and 67.18 ± 0.55% % total dietary fiber (db) was collected from juice sellers in the Mashhad. SDSC with 6.9% moisture (db), 39.24% proteins (db), 4.7% fat, 10.5% ash, Carbohydrate 40.1 ± 0.52% (db) and 8.98% total dietary fiber was supplied by the Boruj oil industry (AOAC, 2000). The dried blend of AP: SDSC mixture in different levels, were coarsely grounded, milled and passed through a sieve with 40 mesh (425 μm). The resulting powder was packed in a polyethylene bag at 25 °C for further usage.

2.2. Extrusion cooking process

The blends of AP and SDSC were prepared at the ratios of 25:75, 50:50 and 75:25 on a dry weight basis. The treatments were formulated by spraying a calculated amount of distilled water to obtain desired moisture levels (14, 18and 22% db.), vacuum sealed in polyethylene bags and stored at 4 °C overnight. Extrusion was performed in a co-rotating twin screw extruder (DS56, Jinan Saxin, China) with feed rate 40 kg/h, length-to-diameter 20:1; nominal compression ratio1:1, and die diameter of 4 mm. The barrel temperature at the transition section was at 140 °C. The final products were dried by oven at 60 °C. The extruders were milled (CG2B, Breville, New South Wales, Australia) and sieved through a 250 μm sieve before analysis [2].

2.3. Analyzing the characteristics of a product

2.3.1. Moisture content

Moisture content (MC) of extruded products (either before or after drying) was measured with a moisture analyzer (HB43–S, Mettler Toledo, Victoria, Australia) [8].

2.3.2. Expansion index

TFI expansion was assessed using the method described by Boluk et al. (2023).The ratio of the average diameter of 10 extrudates to the diameter of the die was measured randomly using a caliper. ER was calculated as follows Eq. (1):

$$\text{Expansion ratio} = \text{Extrudate Diameter/ Die diameter} \tag{1}$$

2.3.3. Bulk density

The volume of the textured sample was measured by the canola transfer method using a 100 ml graduated cylinder. A sample size of 20 g was measured for each test. The ratio of weight to volume replaced in the cylinder was calculated with Eq. (2): [21].

$$\text{Bulk Density} = \frac{\boldsymbol{4m}}{\boldsymbol{\pi d^2 L}} \tag{2}$$

where m is the mass, g of a length L, cm of extruded samples of diameter d, cm.

2.3.4. Hardness

The Lioyd texture analyzer (TA -Plus, England) was performed to measure hardness. From each treatment, 10 samples were randomly selected and placed in the appropriate location. The cylindrical steel probe with a diameter of 2 mm was set to move at a speed of 1 mm/s. The penetration depth was 8 and the load cell was 50 N. The maximum force required to break the puffed products was recorded and analyzed as the amount of hardness. The measurements were reported as the average of five repetitions [1].

Table 1
Independent numerical variables and their levels.

Numerical variables	Symbol	Coded variable levels		
		−1	0	+1
AP: SDSC (W/W)	A	25:75	50:50	75:25
SS (rpm)	B	120	150	180
Moisture (%)	C	14	18	22

2.3.5. *Morphology and microstructure*

The scanning electron microscope (SEM) (VP 1450, LEO Company, Germany) was used to image the cross section of the textured samples. To prepare the specimens, cuts were first made in the cross section with a cutter and then each specimen was fixed on an aluminum support. Then, a thin layer of gold-palladium was applied to the surface of the samples using a coating/spraying device. The cross-sectional images were taken at different magnifications under a pressure of 30 Pa and a voltage of 20 Kv [2].

2.3.6. *Color*

The color of the textured ingredient was measured using a ColorQuest XE (HunterLab, USA). The results were expressed as Hunter color values, L*, a*, and b*. L* represents lightness and darkness, a* represents redness and green, and b* represents yellow and blue [16].

2.3.7. *Water absorption index (WAI)*

A sample of 2.05 ± 0.005 g was placed in a centrifuge tube and 20 ml of distilled water was added. The sample was kept for 15 min (with constant shaking every 5 min) and then centrifuged at 15,000 rpm for 15 min. The supernatant was decanted [22].

The weight of the sediment obtained after separation of the supernatant is as follows Eq. (3):

$$\mathrm{WAI} = \frac{Weight\ of\ wet\ sediment(g)}{Weight\ of\ dried\ sediment(g)} \tag{3}$$

2.3.8. *Antioxidant activity*

The solution extraction method was obtained [23]. First, 1 g of the dried sample, crushed and carefully sieved, then mixed with 20 ml of 80% methanol (V/V). The vortex mixture was used for uniformity and set up at 37 °C with an oscillating water bath at a constant temperature of 5800×*g* for 2 h. After centrifugation at 4000 r/min for 10 min, the supernatant was removed and then stored at 4 °C for use. The ability to inhibit DPPH was determined based on the method reported with some modifications (Donlao & Ogawa, 2018).

2.3.9. *Total phenolic content (TPC)*

The total phenolic content was measured by the Folin-Ciocalteu method as described by Ruiz-Armenta et al. [18]. The results were expressed as mg GAE/g of sample weight, where GAE stands for Gallic Acid Equivalents.

2.3.10. *Physicochemical analysis of the textured functional ingredient and the raw material*

The physicochemical properties of TFI were compared with non-extruded materials at optimal extrusion conditions. Samples were ground using a laboratory mill and passed through a 40-mesh sieve prior to analysis. Dietary fiber content (TDF, SDF, and IDF) was measured using the Megazyme fiber analysis kit (Megazyme International Ireland Ltd, Wicklow, Ireland). Briefly, 1 g of the sample was treated with phosphate buffer and then digested in a water bath by thermostable a-amylase at 100 °C for 15 min and protease and amyloglucosidase at 60 °C for 30 min. After filtration, the residue was dried on the filter at 105 °C and then weighed as IDF. Ethanol was added to precipitate the SDF. The residue was filtered and washed with ethanol and acetone. The precipitate, which was designated as SDF, was dried at 105 °C and weighed. The TDF content was calculated as the sum of IDF and SDF [17].

2.3.11. *Experimental design and statistical analysis*

The central composite design (CCD) is a type of response surface methodology (RSM) used in experimental design to analyze the relationship between multiple variables and a response variable. CCD consists of three types of experimental runs: factorial points, axial points and central points. Factorial points allow the estimation of main effects and interactions, while axial points allow the estimation of curvatures. The center points are used to estimate the pure error. The goal of CCD is to determine the optimal values of the independent variables that lead to the desired response. This can be done through various statistical methods such as regression analysis and optimization algorithms. In current study, Experimental data were analyzed using the Design-Expert 10.0.7. It consists of three numerical independent variables, namely Screw speed (x_1), Feed moisture (x_2), AP: SDSC (x_3), each at three levels, which provided 20 runs (Table .1). ANOVA was used to examine the influence of independent variables on various properties of blends.

3. Results and discussion

Regression analysis and ANOVA were used to select the appropriate model and to examine the statistical significance of the response variables. The adequacy of the model was checked using the coefficient of determination (R^2) and coefficient of variation

Table 2
Coefficient of variables in the suggested model for response variables.

Parameter	Humidity	ER	BD (g/cm3)	Hardness (N)	WAI (%)	L*	AA (%)	TPC (mg/100g)
A	0.0001***	0.0001***	0.0005***	0.0001***	0.0013***	0.0048**	0.3965	0.1853
B	0.7957	0.5361	0.1136	0.0001***	0.1277	0.9902	0.0008***	0.0104*
C	0.0063*	0.0001***	0.2847	0.08063*	0.0348	0.0001***	0.0074**	0.0275*
AB	0.5106	0.0110*	0.0313*	0.0502	0.6620	0.0003***	0.2232	0.0182*
AC	0.2963	0.0424*	0.0995	0.0115*	0.0128**	0.0001***	0.3881	0.0724
BC	0.8781	0.3058	0.0009***	0.0478*	0.0402*	0.0001***	0.0360*	0.0323*
A2	0.5105	–	0.0024**	0.0232*	0.0004***	0.0164*	0.0197*	0.0409*
B2	0.0093***	–	0.0155*	0.0158*	0.1458	0.1302	0.1498	0.3985
C2	0.5427	–	0.4762	0.6758	0.0006***	0.0360*	0.0267*	0.2669
model								
F Value	0.0001***	0.0001***	0.0009***	0.0001***	0.0001***	0.0001***	0.0036**	0.0083**
R2	0.9721	0.963	0.892	0.947	0.941	0.964	0.854	0.824
Adjust R2	0.9470	0.947	0.795	0.901	0.889	0.933	0.722	0.665
Lack of fit	0.8708	0.8072	0.2996	0.5515	0.2153	0.1084	0.1627	0.0502

A = AP: SDSC (%), B=SS (rpm), C = moisture (%).
*Significant at $P < 0.05$; ** significant at $P < 0.01$; *** significant at $P < 0.001$.

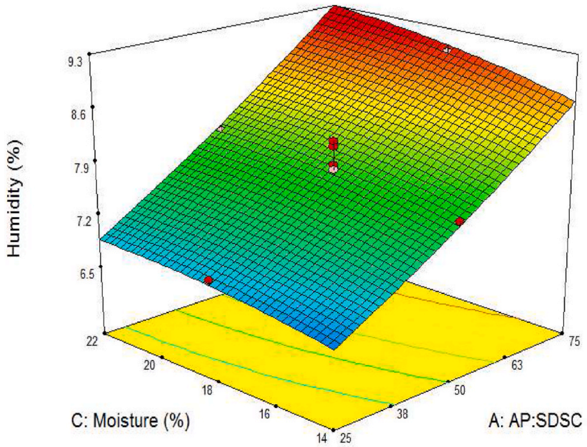

Fig. 1. Response surface plot for the influence of AP: SDSC ratio and moisture content on the Humidity of the textured functional ingredient.

(CV). The lack of fit was not significant for all response variables (Table 2), indicating that these models were accurate for predicting the responses.

3.1. Humidity

ANOVA the results and the proposed fitted model are shown in Table (2). AP:SDSC content and feed moisture had a significant positive linear effect (P < 0.05) on the humidity of the textured ingredients. Only the quadratic term of screw speed was statistically significant (P < 0.05). Although other cereal products such as bread, cakes and cookies have high moisture content, extruded products have low moisture content and long shelf life [12]. The moisture content of AP: SDSC extrudates varied from 6.11 to 9.12%. O'Shea et al. [12] reported the same data for the final moisture range of a puffed fibrous snack based on AP and corn flour (8.43–6.2%). Figure (1) shows that the humidity of TFI increased with increasing ratio of AP:SDSC and amount of feed moisture. As shown in Figure −1, AP:SDSC content was a strong variable affecting the moisture content of the product (P < 0.0001). The highest final moisture content of TFI (9.12%) was recorded for the sample with AP:SDSC level (75%), moisture content of (22%) and SS (180 rpm). During extrusion, the ungelatinized starch forms a weak film and the water remains in the dough instead of evaporating rapidly. Any biopolymer (insoluble fiber and protein) that has a lower expansion can retain moisture in the same way ([22]., O'Shea. et al., 2014). Fruit fibers have a greater ability than cereal fibers to trap water in the cell structure, so the fibers in AP absorb more water due to their high hydrophobicity [12,22]. Therefore, increasing AP had a positive effect on the final moisture content of TFI. The moisture content of TFI is affected by the type of formulation and extrusion conditions such as initial temperature and humidity [24]. An increase in moisture acts as a lubricant and reduces the effects of extrusion temperature on the molten material. Since moisture acts as a plasticizer, it affects all properties of the extrudates [25]. Also due to the hydrophilic compounds in AP, which lead to increased moisture of TFI [22]. similar outcomes were found by Karkle et al. [22] for apple pomace-corn meal based extruded product and Lohani et al. [13].

For the predicted model of the Humidity value, equation can be constructed in terms of coded values as follows:

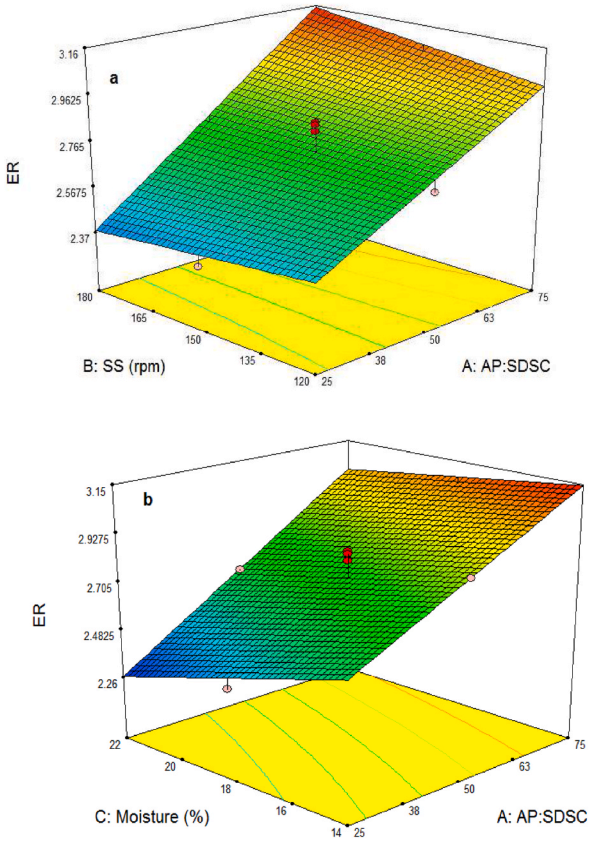

Fig. 2. Response surface plot for the influence of screw speed (RPM)- AP: SDSC content (a) and AP: SDSC content - moisture (b) on the expansion ratio (ER) of the textured functional ingredient.

$$\text{Humidity } (\%) = +7.86 + 1.14 \times A + 0.017 \times B + 0.22 \times C + 0.049 \times A \times B + 0.079 \times A \times C + 0.011 \times B \times C + 0.083 \times A^2 - 0.39 \times B^2 - 0.077 \times C^2$$

3.2. Expansion ratio (ER)

The expansion index expresses the ratio between the diameter of the extrudates and the diameter of the die. This property is related to the extent of puffiness, porosity, hardness of texture, and density (O'Shea et al., 2013). The results from ANOVA and the proposed fitted model are shown in Table 2. The interaction term between AP: SDSC and SS and between AP: SDSC and moisture was significant for ER ($P < 0.05$). The coefficients of determination (R^2) for moisture content 0.963 and R2 (adj)for moisture content 0.947, while lack of fit was not significant ($P > 0.05$). The values of ER varied from 2.22 to 3.18. Similar results were reported by Ref. [1,12,26] for apple pomace (2.5–4.54), mango pulp (2.19–4.09), carrot pulp (1.22–3.8). The highest value of ER (3.18) belonged to the sample with the highest proportion of AP: SDSC (75:25) and the lowest moisture content (14%) and the highest SS (180 rpm). Figure (2-a) shows that increasing the proportion of AP had a significant increasing effect on ER. This could be due to the high content of soluble fiber (pectin) in the structure of AP. The presence of pectin in AP has the ability to form a viscoelastic mass during the extrusion process due to its high water solubility, and increasing SS could result in puffing, sufficient porosity, and an increase in extrudate volume ([13,27] and Ačkar et al., 2018). In contrast, insoluble fibers, fats, and proteins present in the structure of SDSC may prevent the formation of intermolecular networks between starch and water [2]. Figure (2-b) shows that decreasing the moisture content from 22% to 14% significantly increases ER at the lowest level of AP (10%). At lower moisture content, the drag force increases, which in turn exerts more pressure on the die, resulting in more expansion of the extruded product at the exit and also increasing the viscosity and elasticity of the compound. The development of a cellular matrix in TFI depends on the extent of expansion, formation or destruction of air bubbles in the molten material [22]. However, as the extrusion temperature increases, the pressure difference increases as more force is applied to increase the volume and create a porous structure in the extruded product [22,26]. The same result was observed by Lohani et al. (2017) for puffed samples with 22% and 30% AP, respectively, although Nascimento et al. [15] reported opposite results for extrudates with 20% SDSC.

The equations of the fitted models after neglecting the effect of non-significant factors for the un coded form of the process variables were as follows:

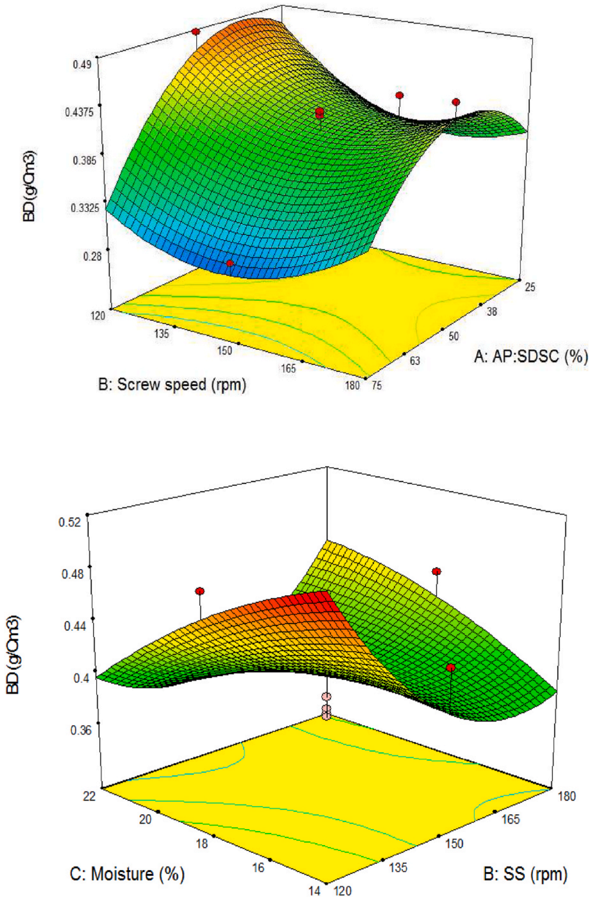

Fig. 3. Response surface plot for the influence of screw speed (RPM)- AP: SDSC content (a) and screw speed (RPM)-moisture (b) on the bulk density of textured functional ingredients.

$$ER = +2.76 + 0.32 \times A + 0.012 \times B - 0.12 \times C + 0.063 \times A \times B + 0.047 \times A \times C + 0.022 \times B \times C$$

3.3. Bulk density (BD)

Bulk density indicates the extent of volume increase and puffiness in all dimensions of the extruded product (Altan, 2008 a; Yağci & Goeğoeş. 2011). ANOVA Results for BD can be found in Table 2. The values of R2 and adj-R2 were 0.892 and 0.795, respectively, indicating a higher coefficient of determination. The F value for BD was significant ($P < 0.01$), whereas lack of adjustment was not ($P < 0.05$).

The AP: SDSC level had a significant negative linear effect ($P < 0.05$), and the interaction term between AP: SDSC and SS and between humidity and SS was significant ($P < 0.05$) on BD. The BD of AP: SDSC extrudates varied between 0.259 and 0.511 g/cm3. Similar results were reported for extruded products based on apple pomace, soybean meal and corn meal (0–521.31 g/cm3) by (Singha & Muthukumarappan et al., 2018) and apple pomace - corn meal (0–46.12 g/cm3) [12].

Figure (3) shows the simultaneous effect of the two variables AP: SDSC and SS on BD of the puffed fibrous snack. The BD decreased when the content of AP in feed increased. Also, increasing SS from 120 rpm to 150 rpm had a negative effect on BD.

The insoluble fibers in SDSC reduce the elasticity and viscosity of the dough due to their hydrophilic properties and high tendency to absorb water [15,17]. The presence of insoluble fibers also collapses the cell walls of air bubbles and prevents the formation of air bubbles the bubble formation system [16]. On the other hand, the pectin in AP has a positive effect on the formation and growth of air cells and increases the desired volume in the extruded product [12]. A high proportion of AP: SDSC leads to a lower density structure in TFI. Sun et al. (2015) reported similar results for puffed products containing AP products. The SS affects the shear rate and the residence time of Molten dough in the shell. Increasing SS and shear stress decreases the viscosity of the mixed materials and nucleation centers increase, ultimately stimulating starch gelatinization and fiber breakage ([3], O'Shea., 2013, Yağci & Goeğoeş., 2011). Excessive SS and high mechanical energy also increased the risk of biopolymer damage. The results of Singha and Matokumarapan [14]. also showed a decrease in BD by increasing SS from 100 to 200 rpm in the samples containing AP. As shown in Fig. 3, the lowest BD (0.239 g/cm3) was obtained when the process conditions were 14% moisture (minimum) and 180 rpm SS (maximum). The

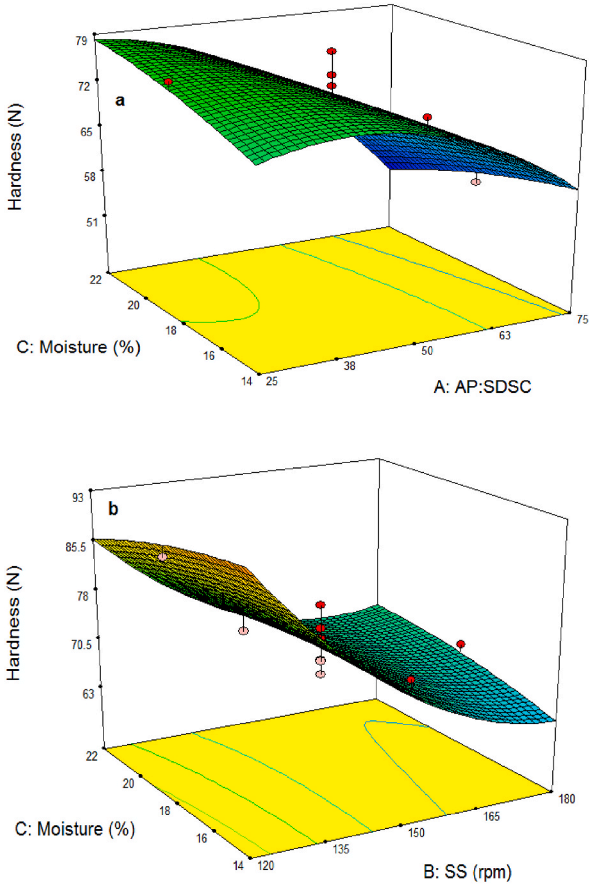

Fig. 4. Response surface plot for the effect of Moisture-AP: SDSC content (a) and screw speed (RPM)-moisture (b) on the Hardness of textured functional ingredient.

reduction of moisture increases the friction between the dough and the spiral and also increases the temperature of the dough, the density decreases and the porosity increases [26]. Products with high density have a thick cell wall, which is directly related to the hardness of the extruded product. Therefore, increasing BD and decreasing the expansion increases the hardness of the puffed fibrous ingredient [27].

The fitted model for bulk density (BD) based on the coded levels of the variables is presented in below Equation

$$BD\,(g/Cm3) = +0.40 - 0.046 \times A - 0.016 \times B - 0.010 \times C + 0.026 \times A \times B + 0.019 \times A \times C + 0.047 \times B \times C - 0.070 \times A^2 + 0.051 \times B^2 - 0.013 \times C^2$$

3.4. Hardness

Hardness analysis is a critical quality control parameter in extrudates that helps manufacturers optimize their formulations, ensure product quality, and meet consumer expectations. The hardness of the TFI obtained in current project varied from 52.99 N to 98.87 N. (4-a). The key quality control parameter in extrudates is hardness analysis, which helps manufacturers are optimizing their formulations, ensuring the quality of the product and meeting the needs of the consumer expectations. The hardness of the TFI obtained in the current project varied from 52.49 N to 52.89 N. 98.87 N. The ANOVA obtained from the regression analysis demonstrated that the quadratic terms of AP: SDSC content, SS, and the interactions of AP: SDSC content - moisture, and moisture content-SS, significantly influenced the hardness of puffed fibrous ingredient ($P < 0.05$). Moreover, the high degree of certainty ($R^2 = 0.947$) and (adjusted $R^2 = 0.901$) indicates that the model describes the relationship well.

The positive coefficient of the moisture content of the feed affected the hardness, and was much reduced with increased AP content. The high content of pectin as a soluble fibre in AP and its lubricating properties have been associated with higher clarity, porosity and hardness [10]. O'shea et al. [12] also reached the same conclusion. Due to the plasticization of the melt, which is influenced by the improvement of feed moisture content, the elasticity of the dough decreases, resulting in a more compact or less porous structure. This reduces the starch's gelatinization, which also affects its expansion and contributes to a higher moisture retention. The increase in hardness due to the high presence of SDSC is caused by the content of proteins and insoluble fibers, which are responsible for the reduction in cell wall thickness and its rapid breakup ([15] and Ačkar et al., 2018). This finding is consistent with work on fiber

Table 3
Experimental design layout and results of color for extruded treatments.

Independent variables			Response variables		
AP:SDSC (A)	Screw speed (B)	Feed moisture (C)	L*	a*	b*
25	200	22	42.17	4.58	19.48
25	200	14	43.48	4.9	19.93
25	120	14	44.16	4.05	18.69
25	160	18	42.95	4.06	18.41
25	120	22	44.55	3.82	17.99
50	160	18	28.71	3.74	10.99
50	160	18	25.75	4.14	9.6
50	160	18	26.4	3.9	10.1
50	160	18	28.71	3.74	10.99
50	120	18	29.9	3.3	9.12
50	160	18	29.1	3.9	11.2
50	160	22	27.34	3.87	12.03
50	160	14	29.09	3.89	11.34
50	200	18	26.77	3.79	9.18
50	160	18	26.8	4.11	10.1
75	120	22	22.31	2.56	4.9
75	200	22	22.16	3.12	6.8
75	120	14	21.43	2.55	5.24
75	160	18	21.33	2.66	5.49
75	200	14	21.1	2.4	5.8

products based on SDSC [16,18,27].

The hardness of the finished product was raised due to a reduced expansion as a result of an increase in the percentage of byproducts in the preparation [9]. For example, the higher percentage of mango husks has resulted in an 8% increase in the hardness of the extrusion product [28]. In grape pomace, tomato pomace and broccoli trimming studies the same results were noted (Altan et al., 2008a, b). Figure (4) confirms that increasing SS has a significant effect on reducing hardness. This phenomenon may be caused by a decrease in melt viscosity and the release of Superheated Steam which leads to more bubbles being formed at the end extrudates. Ding et al. [29] has also reported similar findings. The interaction between SS and feed moisture is shown in Figure (4). By reducing the gelatinization and decreasing the elasticity of the molten dough, higher moisture content increases hardness (Thymi et al., 2005; [26]).

The equation of the fitted model is shown as follows:

$$\text{Hardness (N)} = +72.31-9.15 \times A-11.24 \times B-0.30 \times C + 2.94 \times A \times B -4.07 \times A \times C + 2.97 \times B \times C-6.02 \times A^2 + 6.53 \times B^2-0.97 \times C^2$$

3.5. Color

Color is an important factor in determining food quality. Color characteristics are evaluated in three groups: L*, brightness; a*, red to green color; and b*, yellow to blue color [21]. The multiple quadratic regression equation for brightness is shown in Table 2. The L* value of TFI was significantly ($P < 0.01$) affected by linear terms of AP: SDSC and humidity, quadratic terms of humidity, and the interactions of all three factors.

L * of TFI ranged from 61.35 to 69.25. The regression model had a coefficient of determination (R^2) and adjusted R^2 value of 0.96 and 0.933, respectively, indicating a higher coefficient of determination. Table 3 shows the interaction of moisture and SS at constant AP: SDSC value on L*. The brightness decreased with increasing SS at the minimum feed moisture (14%). Table 3 confirms that increasing AP: SDSC content and moisture had negative effects on L*. However, L* of TFI increased simultaneously with the increase of SS and moisture. Increasing the temperature, increasing SS and increasing the fiber content at low moisture increased the browning response and decreased the brightness L* (Alam et al., 2016). The decrease in L* of TFI by increasing SS was influenced by the breaking of starch bonds and the contribution of more sugars in the Millard reaction [25]. Carvalho et al. [16] reported that half defatted sesame seed cake (SDSC): maize extrudates were darker than raw samples, due to the high content of brown pigments present, particularly in sesame oil cake.

Naumann et al. [30] and Huang et al. [31] investigated similar results on the effects of pineapple seed fiber on the color of mantou, carrot pomace powder on the color of cookies, less brightness in lupin seed fiber, and less brightness in defatted extruded quinoa flour, respectively. Similar studies have shown that color changes during the extrusion process [5] are related to Millard, caramelization, and hydrolysis pigment degradation during extrusion [21,32].

The equation of the fitted model is presented as follows:

$$L* = +67.74 + 0.57 \times A + 2.000E\text{-}003 \times B-1.37 \times C + 0.96 \times A \times B-1.14 \times A \times C + 1.30 \times B \times C-0.88 \times A^2-0.50 \times B^2-0.74 \times C^2$$

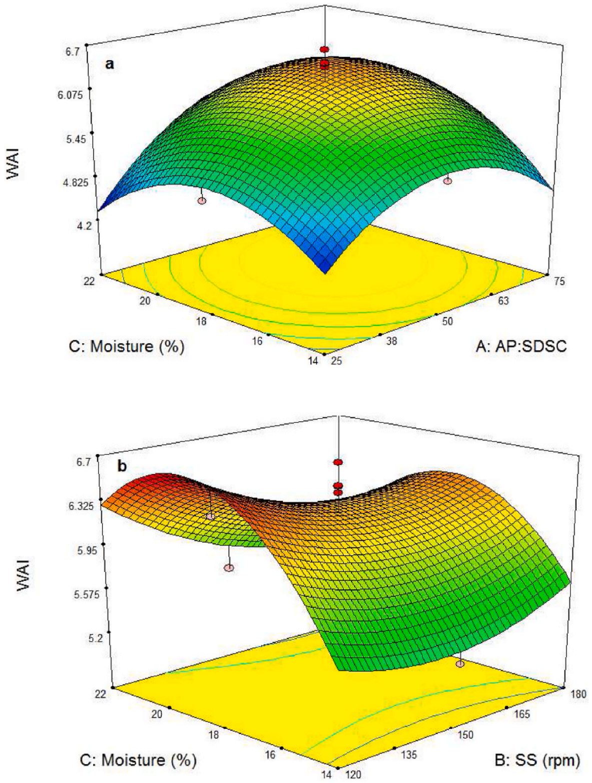

Fig. 5. Response surface plot for the effect of Moisture-AP: SDSC content (a) and screw speed (RPM)- Moisture (b) on the WAI of textured functional ingredient.

3.6. Water adsorption index

The water absorption index (WAI) is a parameter that refers to the degree of change of macromolecules in thermally processed foods such as starch and dietary fiber (Lotfi et al., 2020). In general, WAI examines the hydrophobicity and hydrophilicity of extruded products, which are affected by starch degradation, protein denaturation, and fiber hydration dynamics [16]. The ANOVA showed that WAI depends significantly ($p < 0.01$) on the linear and quadratic terms of AP: SDSC level and moisture ($p < 0.05$) and on the interaction of AP: SDSC level and moisture, SS and moisture ($p < 0.01$). The values of R^2 and adj-R^2 were 0.941 and 0.889, respectively, suggesting a higher coefficient of determination.

The WAI of TFI varied from 4.373 to 6.643 g/g. As shown in Fig. 5, WAI increased up to 18% when moisture content was increased and AP: SDSC increased up to 25%, but this process changed drastically and the maximum values of both variables decreased. This could be due to the increase in swollen crude fiber, which plays an important role in increasing WAI (Santillán-Moreno et al., 2009).

Cellulose, hemicellulose, and pectins are the main components of apple pomace. Unlike cellulose, hemicellulose and pectin are partially water soluble; due to the amount of pectin polymers and water-soluble hemicelluloses, there is an increase in water solubility, which has also been demonstrated for orange peel fiber [30]. During extrusion, dissolution of pectin decreases the amount of arabinose and galactose [13]. Extrusion may result in lower proportions of galactose and arabinose in the water-insoluble residues, indicating dissolution of pectic substances during the extrusion process [14]. It is likely that WAI increased due to the change in cell wall structure and its opening during extrusion. In addition, the higher degree of porosity leads to greater water absorption during rehydration [11].

Fig. 5 shows the interaction of SS and moisture on the WAI. According to the data, the thermal-mechanical treatment during extrusion partially destroyed the cell wall, which in turn led to easier and greater penetration of water into the granules and caused the dissolution of the soluble fraction. As a result, there was increased gelatinization and depolymerization of the starch molecules, which increased the WAI (Wang et al., 2012 and [30]). These data are consistent with the study of Redgwell et al. [33], who investigated the water retention capacity of apple pomace after shear treatment. However, WAI gradually decreased, which was largely dependent on moisture improvement. In general, it has been studied that the WAI of hydrophobic and hydrophilic extruded products is affected by starch degradation, protein denaturation, and fiber hydration dynamics [22]. Similar results were reported by Ačkar et al. (2018) for extruded corn. Simultaneous increase in screw speed and feed moisture content resulted in higher water adsorption of extruded samples. Fig. 4 illustrated that the WAI of extrudates decreased with increasing screw speed at high moisture content. Moisture content at higher values reduces the protective plasticizing effect of water in the extrudate and enables the high energy input of extrusion that separates the amylose and amylopectin chains [30].

The predicted quadratic model for the WAI of extruded sesame flour (ESF) was as follows.

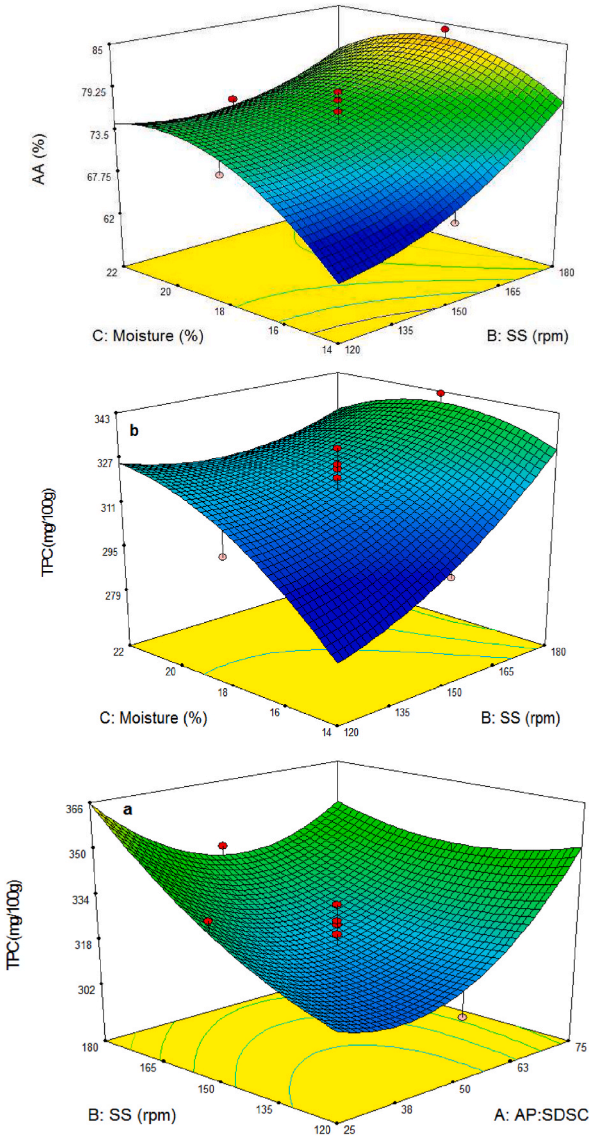

Fig. 6. Response surface plot for the effect of SS - Moisture (a) on the AA, the effect of SS -AP: SDSC content (b) and SS - Moisture (c) on the TPC of textured functional ingredient.

$$WAI = 6.26 + 0.35 \times A - 0.13 \times B + 0.19 \times C + 0.040 \times A \times B + 0.27 \times A \times C - 0.21 \times B \times C 0.78 \times A^2 + 0.24 \times B^2 - 0.74 \times C^2$$

3.7. *Total phenolic content (TPC) and antioxidant activity (AA)*

Antioxidant activity indicates the ability of a bioactive compound to maintain cell structure and function by effectively removing free radicals, inhibiting lipid peroxidation reactions, and preventing other oxidative damage [11,23]. The values of antioxidant activity (AA) ranged from 26.2 to 54.1%. Regression analysis showed that the antioxidant activity of TFI was significantly ($P < 0.05$) affected by positive square terms of moisture, and SS and their interactions. The lack of adjustment was found to be non-significant ($P > 0.05$) for TAA of TFI. The changes in antioxidant activity of TFI levels with moisture and SS are shown in Fig. 6-a. Increasing the moisture content up to 20% had a positive effect on antioxidant activity at a minimum SS of 120 rpm. However, a higher moisture content had a negative effect on antioxidant activity. Increasing SS from 120 to 150 rpm and at a minimum moisture content of 14% increased the antioxidant activity of TFI. However, the antioxidant activity further decreased at 150–180 rpm. The results of Zhang et al. (2019) showed a remarkable reduction in phenolic acid levels. Similar results were reported by Yaqsi and Gogos (2008) for extruded products with fat-free hazelnut meal and fruit pomace and by Bisharat et al. (2014) for products with broccoli and olive pomace.

The TPC for the TFI ranged from 295.6 to 390.4 mg/100g. The model equation predicting the response is shown in Table 2. TPC was

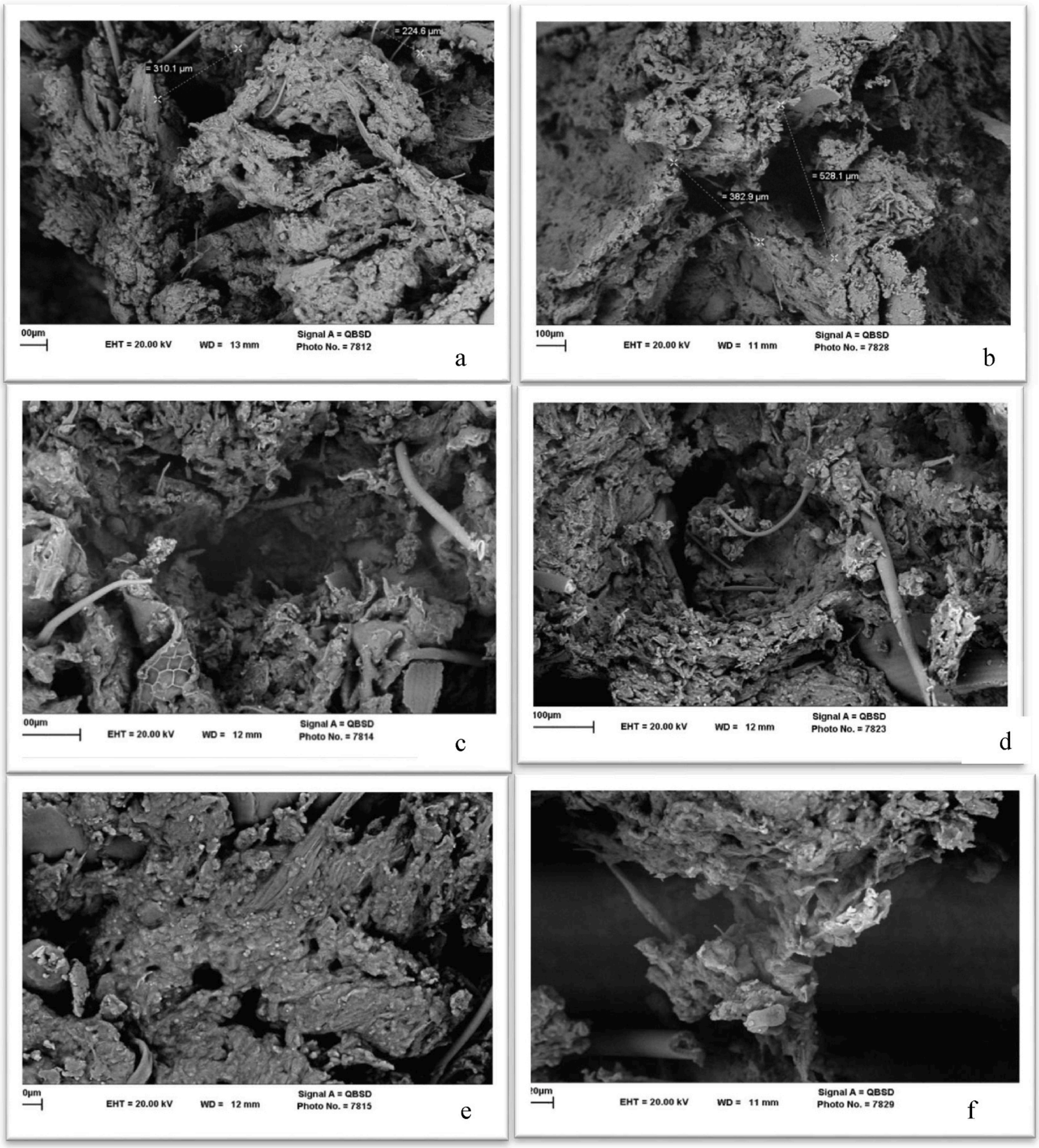

Fig. 7. Scanning electron micrographs of TFI at AP: SDSC, (25: 75%), 250 magnification (a), AP: SDSC, (50: 50%), 250 magnification (b), AP: SDSC, (25: 75%), 500 magnification (c), AP: SDSC, (50: 50%), 500 magnification (d), AP: SDSC, (25: 75%), 2000 magnification (e), AP: SDSC, (50: 50%), 2000 magnification (f).

significantly affected by the quadratic terms of SS and moisture content, as well as by the interactions of AP: SDSC level and SS and moisture content and SS ($P < 0.05$). The values of R^2 and adj-R^2 were 0.824 and 0.665, respectively, which is a good coefficient of determination.

A study of the effects of extrusion conditions on the TPC of extrudates showed that 80–97% of polyphenols were retained compared to the crude blends. Fig. 6-b shows that increasing SS increases TPC activity, while this response also increases with increasing feed moisture and reaches a maximum value (Fig. 5). However, different researchers have reported an increase in TPC and antioxidants in extruded products, due to the release and generation of antioxidant compounds and the inactivation of enzymes responsible for the oxidation of these types of compounds [34,35]. The high retention has been attributed to the combined effects of feed moisture, shear stress, and temperature, which degrade the compounds or cause their conversion to easily extractable forms [18].

Espinoza-Moreno et al. [34] reported that the increase in antioxidant activity could be due to the release of antioxidant phenolic compounds during the extrusion process, the prevention of oxidation of phenolic compounds in the extruded product by enzymatic inactivation during processing, and the presence of Maillard reaction products. The presence of amino acids and reducing sugars in the raw materials and the use of high temperatures during processing allow the formation of high molecular weight complexes e.g., melanoidins, that have been associated with antioxidant properties. Some authors have reported the presence of melanoidin precursors

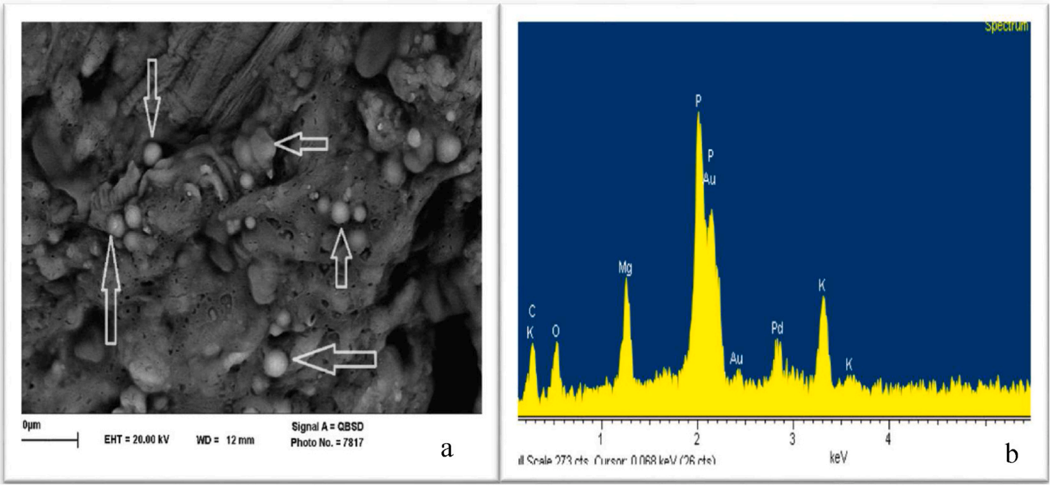

Fig. 8. Microstructure of TFI at AP: SDSC, (25: 75%), 5000 magnification (a), XRD profiles of TFI at AP: SDSC, (25: 75%) (b).

in extrudates reported an increase of AA after extrusion in quinoa and sesame by-products, respectively [11,18,35].

The predictive model for TPC and AA was the following:

$$TPC = +318.32 + 6.09 \times A + 13.46 \times B + 11.04 \times C - 13.49 \times A \times B + 9.61 \times A \times C11.89 \times B \times C + 19.15 \times A^2 + 7.20 \times B^2 - 9.60 \times C^2$$

$$AA = +45.23 + 0.70 \times A + 5.03 \times B + 3.10 \times C - 1.72 \times A \times B + 1.28 \times A \times C - 3.00 \times B \times C + 5.28 \times A^2 + 2.93 \times B^2 - 4.62 \times C^2$$

3.8. Morphology and microstructure

Scanning Electron Microscope (SEM) images examine the microstructure including size, number and wall thickness of air cells; In addition, X-ray energy diffraction (EDX) was used to analyze the chemical properties of the samples [15]. The variable of AP: SDSC was the most effective factor for macrostructural features such as ER and hardness. Therefore, microscopic images of the extruded product with minimum and maximum values of AP were obtained: SDSC, (25: 75%) and (75: 25%), respectively. Fig. 6 shows the effects of the different ratios of AP: SDSC at constant moisture content (18%) and a SS 150 rpm with magnifications of 250 (Fig. 7-a, b), 500 (Fig. 7-c, d), and 2000 (Fig. 7-e, f). The extrusion disturbed and changed the macroscopic structure of the cell walls, resulting in more porous structures. Fig. 7-a, b shows a relatively porous structure with uneven texture and with holes and heterogeneous cells. These observations are consistent with the results of Lohani et al. [13] and Sun et al. (2015) for extruded apple pulp. The samples with the highest values of AP have more specific and regular air cells than the samples with the lowest values. Increasing the content of AP at constant process conditions results in more air bubbles with thinner cell walls and larger diameter (Lohani et al., 2017). Diameters of 6.224 and 1/310 µm were observed in samples with high SDSC content, and relatively more uniform air cells with a distinct wall and diameters of 9.382 and 1.528 µm were observed in samples with high AP content (Fig. 6-b). In fact, a more regular porous sponge structure was observed due to the high proportion of pectin-soluble fibers in the samples with a AP: SDSC ratio of 75:25% compared to the samples with a AP: SDSC ratio (25:75%). Pectin decreases the destruction of the air walls and increases the nucleation centers [27]. Yanniotis et al. [27] reported that with increasing amount of insoluble fibers, more air bubbles with smaller size and larger wall thickness lead to the development and expansion of air walls. Also, Nascimento et al. [15] indicated that the size of air cells and the thickness of walls decreased by increasing the amount of insoluble fiber in SDSC. According to the results of other authors, there is a significant relationship between the physical properties (porosity, density and expansion ratio) and the hardness of the samples and the parameters studied in the microscopic measurements [24]. Samples with lower ER and higher hardness have microscopically smaller air cells and thicker cell walls [29]. These results are consistent with the analysis of hardness and ER. Similar results were observed for puffed products from AP (Sun et al., 2015) and SDSC (Nascimento et al.,0.2012). In Fig. 8, at 5000x magnification, the sample with the highest SDSC content (AP: SDSC, 25: 75%) had the highest number of bright spots. Due to the high probability of the presence of minerals in these areas (these spots are marked with an arrow in the image), these samples were analyzed by X-ray energy diffraction spectroscopy to determine the mineral content in the bright spots. Fig. 8 confirms the presence of large amounts of minerals such as phosphorus, potassium and magnesium in the samples. This confirms that sesame flour is rich in minerals. Nascimento et al. [15] also reported the presence of large amounts of minerals (calcium, phosphorus, potassium, and magnesium) in SDSC.

3.9. Optimum extrusion condition

The optimal values of the independent variables can be effectively selected in central composite design analyses to achieve the

Table 4
The physicochemical analyzes of the textured functional ingredient and the raw materials.

Properties	Fiber supplement containing apple pomace-sesame oil cake	
	Untreated ingredient	Optimal TFI
Moisture (%)	$0.96^{a}\pm7.8$	$0.14^{ab} \pm 6.51$
Protein (%)	$0.12^{a}\pm 38.63$	$0.01^{b} \pm 34.15$
Fat (%)	$0.45^{a}\pm 5.06$	$0.08^{a}\pm 4.58$
Water absorption index (g/g)	$0.07^{ab} \pm 5.90$	$0.05^{a}\pm 6.00$
Oil absorption index (g/g)	$0.11^{a}\pm 2.92$	$0.2^{a}\pm 2.43$
Bulk density (grams per cm^3)	$0.32^{a}\pm0.55$	$0.01^{b} \pm 0.51$
Soluble dietary fiber (%)	$0.05^{b} \pm 10.08$	$0.13^{a}\pm 11.12$
Insoluble dietary fiber (%)	$0.1^{a}\pm 43.95$	$0.07^{b} \pm 39.30$
Total soluble dietary fiber (%)	$0.56^{a}\pm 54.05$	$0.55^{b} \pm 50.42$
Total count of organisms (colonies per gram)	$106^{a} \times 2.82$	$103^{b} \times 0.3$
The number of mold and yeast (colonies per gram)	$105^{a} \times 1.5$	0^{b}
Acidity during zero period (oleic acid in 100 g)	$0.11^{a}\pm 25.34$	$0.37^{b} \pm 19.05$
Acidity during the storage period of 30 days	$0.61^{a}\pm29.09$	$0.23^{b} \pm 21.96$

desired response. For this purpose, to obtain a TFI with the maximum values of ER, brightness, WAI, AA and TPC as well as the minimum hardness and bulk density, the optimum conditions were determined at 176 rpm SS, 18% feed moisture and a (75:25) AP: SDSC mixture with a desirability value of 0.801. Thus, the desirability value indicates a reasonable match between the predicted and observed response. To confirm the predicted values, an additional experiment was conducted. It contributes to the validation of the model and ensures that the optimal values are reliable. In this work, the predicted values (ER = 3.745 %, WAI = 5.904 g gel/g sample, TPC = 348.248 mg GAE/100g dry sample, AA = 86.501%, BD = 0.327 g/cm3, L* = 67.999 and Hardness = 54.992 N) and experimental values (ER = 3.133 %, WAI = 6.001 g gel/g sample, TPC = 351.113 mg GAE/100g dry sample, AA = 88.003%, BD = 0.407 g/cm3, L* = 66.258 and Hardness = 55.132 N) were similar and based on t-test analysis (SPSS Statistic 22), there was no significant difference between the values predicted by the model and those actually obtained during validation ($p \leq 0.05$).

3.10. Physicochemical analysis of the textured functional ingredient and the raw material

Table 4 compares the physicochemical analyzes of the textured functional ingredient and the raw material by a 95% confidence t-test analysis. The values for WAI and soluble dietary fiber were higher for Optimal TFI than for the untreated ingredient. The total dietary fiber content of Optimal TFI decreased due to conversion of insoluble fiber to soluble fiber (Sayanjali et al., 2017). Shear forces cause dietary fiber to break down into lower molecular weight compounds, often decreasing the insoluble dietary fiber fraction in favor of the soluble fraction (Boluk et al., 2023). Microbial analysis also showed that the total number of microorganisms and the number of molds and yeasts in the sample were significantly reduced after extrusion. This 4 also shows that the extruded sample may have a positive effect on the 30-day shelf life due to its low acidity. The TFI could be used to produce functional foods such as porridges, beverages, cookies, soups and others, which could provide health benefits due to the values obtained.

4. Conclusion

The increasing attention towards utilization of byproducts is evident from the substantial number of research publications in the past decade. The present study demonstrates the successful modification and functionalization of valuable residues such as apple pomace and sesame oil cake through extrusion processing. The analysis of functional properties revealed that optimal treatment resulted in a significant increase in water absorption and soluble dietary fiber by up to 22.3% and 10.3%, respectively. The SEM results confirmed that extrusion processing induced modifications not only at the molecular level but also at the macromolecular level, resulting in an increase in porosity of the samples. This could explain the observed increase in water absorption index (WAI).

The microstructure analysis of TFI indicated the presence of fibrous structures, suggesting that extrusion processing increased the surface area and porosity of the samples. This enhanced porosity could facilitate the penetration of water into the cell walls and contribute to the dissolution of the soluble fraction. The results of the validation experiment demonstrated a high degree of agreement between the predicted and observed response variables, indicating that extrusion processing is an effective technology for enhancing the functional, nutritional, and nutraceutical properties of TFI. The extruded flour obtained under optimal conditions could serve as a potential ingredient for the production of functional foods and beverages. Further research is warranted to thoroughly characterize the sesame by-product flour and investigate the impact of optimal extrusion conditions on other chemical, physicochemical, techno-functional, nutritional, and nutraceutical properties of the flour.

CRediT authorship contribution statement

Elnaz Milani: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Investigation, Data curation, Conceptualization. **Neda Hashemi:** Writing – original draft, Visualization, Software, Resources, Funding acquisition, Formal analysis, Data curation. **Asieh Ghiafehshirzadi:** Visualization, Methodology, Funding acquisition, Data curation, Validation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Elnaz milani reports financial support was provided by Academic Center for Education Culture and Research. Elnaz Mialni reports a relationship with Elnaz Milani that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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