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Research Article

Characterization of a Mixture of Oca (*Oxalis tuberosa*) and Oat Extrudate Flours: Antioxidant and Physicochemical Attributes

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The oca (*Oxalis tuberosa*) is a tuber with high starch content and excellent antioxidant properties, which can be used in the production of extruded products; however, starch-rich products can be improved nutritionally through the incorporation of fibers that can result in extrudates with beneficial health properties. The aim of this work was to develop a mixture of oca (*Oxalis tuberosa*) and oat extrudate flours and evaluate the antioxidant and physicochemical attributes. The results showed that a higher moisture content increased the hardness, water absorption index, and density of the extrudates; however, the solubility and expansion indexes showed an inverse pattern. The addition of oat fiber had the opposite effect from moisture content on the physicochemical properties mentioned above. The cellular antioxidant activity (CAA) of the extrudates decreased when the oat fiber increased. An inverse pattern was observed when the moisture concentration was increased. The starch hydrolysis percentage and glycemic index decreased significantly when the fiber content increased. Oat fiber contributed 67.29% and 65.04% to these parameters, respectively. Oat fiber exerted a greater effect than moisture on the collets extruded in this study according to factor contributions.

1. Introduction

Extrusion is one of the most versatile and efficient technologies used for the production of processed foods. It is used to continuously convert raw materials into finished products. Food extrusion equipment uses thermomechanical energy to induce physicochemical changes in food similar to those from mixing and homogenization [1]; these changes result in a significant retention of nutrients, a reduction of microbial contamination, the inactivation of some antinutritional factors such as trypsin, tannins, and phytates [2, 3], and an increase in the digestibility of food [4]. Special consideration is being given to increased dietary fiber content, mainly in grain-based products such as snacks and breakfast cereals [5, 6].

Extrusion technology is widely used to make ready-to-eat breakfast cereals and snacks, pasta, modified starch, and textured vegetable proteins [7]. Extruded puffs, or collets, are usually generated from refined milled fractions of cereal grains and in some instances, whole-grain meals. Corn (flour or grits) is one of the most commonly used feedstocks in the elaboration of expanded, extruded food products. However, Silva et al. [8] mention that the nutritional values of cornflour and other cereals do not satisfy the health needs of consumers. Alternatives include the use of blue and white corn, yellow peas, and oat bran in extruded food products. The increasing use of colored grains is due to their higher content of anthocyanins and phenolic compounds, which are associated with the prevention of chronic and degenerative illnesses such as cancer,

cardiovascular disease, and cataracts [9, 10]. These authors reported that the beneficial effects of flavonoids (compounds found in colored potatoes) were not significantly affected in the extrudates compared to raw food. This information indicates that nonconventional tubers can be used in the production of thermoplastically extruded functional foods. Oca (*Oxalis tuberosa*) is an endemic crop of the Andes. Approximately two hundred years ago, the cultivation of oca was introduced to Mexico [11], but its use in extruded food products has not been reported before. Oca is one of the least-studied nonconventional tubers. Chirinos et al. [12] reported that the fresh weight (FW) of purple oca contained 161.8 mg GEA/100 g FW of total phenolics, 10.7 mg CE/100 g FW of total flavonoids, 47.4 mg CGE/100 g FW of total anthocyanins, and 8.9 μm TE/g FW of antioxidant capacity. Hernández-Lauzardo et al. [13] reported up to 90.5% starch with a B-type X-ray diffraction pattern and 33% amylose in the starch of this particular tuber. Its high starch content and excellent antioxidant properties could make oca tuber an excellent raw food material for the elaboration of extruded food products. However, the oca tuber has low fiber content (~10%), and several studies have reported that the addition of dietary fiber in extrudate products contributes to the reduction of coronary heart-related disease, diabetes, and colorectal cancer [14]. On the other hand, the addition of dietary fiber negatively contributes to the organoleptic and technological properties of the extruded products [15].

The combination of purple oca flour and oat fiber may produce healthy snack foods incorporating natural color along with positive effects on human health. There are no studies showing the effect of fiber and moisture concentration on extruded oca flour. To find the proper concentrations of oca flour and oat fiber, as well as moisture content, in the extruded product, a central composite study was designed. The aim of the present study was to evaluate the effect of different concentrations of oat fiber and tempering moisture on starch digestibility, glycemic index, and the physical, textural, and mechanical properties of extruded oca tuber samples.

2. Materials and Methods

2.1. Materials. Purple oca tubers (*Oxalis tuberosa* Mol.) were purchased from a local market in Tulancingo Hidalgo, Mexico. The tubers were first washed with tap water and then cut into 1 cm slices. The slices were dried at 40°C for 24 h in a convection oven, ground using a commercial grinder (Oster-BPST02-B00, Mexico, D. F), passed through a US #20 sieve (0.841 mm), and stored at 25°C in plastic bags until further analysis. The dietary fiber and cellular antioxidant activity of oca flour before the extrusion process were 10.51% db and 76.36 units, respectively, and the chemical composition was total carbohydrates 82.7%, protein 1.9%, ether extract 1%, and ash 6.1%.

The oat fiber (Vitacel®, HF 401) was donated by J. Rettenmaier USA LP. Nutritional information of oat fiber % (g/100 g) included total fiber 86.2, insoluble fiber 83.9, soluble fiber 2.3, total carbohydrates 86.9, protein 2.15, and light yellow color. The moisture contents of the oca flour and oat fiber were 8.1 and 9.1%, respectively.

2.2. Extrusion Process. Table 1 depicts the different treatment combinations. The different mixtures were extruded with a twin-screw corotating extruder (BCTM-30, Bühler, Uzwil, Switzerland) equipped with a pair of 800 mm screws with a length-to-diameter ratio of L/D = 20 at a solid matter feed rate of 25.6 kg/h (db). The moisture content was controlled by the automatic liquid feeder of the extruder according to Table 1. A die with a single hole with a diameter of 4 mm was used, and the screw configuration was specifically selected for high levels of shear stress.

The first section contained only conveying elements, while the next section contained both conveying and mixing elements. The high-shear section contained conveying and reverse conveying elements and one kneading element. The cutter speed was set at 300 rpm for all trials. During the final stage of the extrusion process, the temperature of the last zone of the barrel was controlled using a TT-137N heater exchanger (Tool-temp, Sulgen, Switzerland). The screw speed was set at 250 rpm, and the temperature of the last zone of the barrel varied between 145°C and 155°C. After reaching stable conditions, the different extrudates were collected and dried for 15 min in an air oven at 80°C. The extruded samples were then stored in plastic bags at room temperature for further analysis.

2.3. Water Absorption (WAI) and Water Solubility (WSI) Indexes. WAI and WSI were determined following the method described by Anderson et al. [16]. A milled sample (2.5 g) was mixed with 10 mL of distilled water in a centrifuge tube, which was vigorously stirred in a standard laboratory vortex mixer until complete dispersion was reached and then placed in a shaker for 30 min at 30°C. Then, the resulting suspension was centrifuged at 6000 × g per 5 min. The WAI was expressed as the weight of the wet pellet per gram of sample. The supernatant was dried in an oven at 105°C until a constant weight was obtained. The WSI was expressed as the percentage of dry solids in the supernatant per gram of original sample.

2.4. Expansion Index (EI) and Bulk Density (BD). The expansion or radial index was measured using a Weston digital caliper Weston STW-1116–150 (Weston, Monterrey, Nuevo León, Mexico) and calculated as the ratio of the extrudate diameter to the extruder die diameter (4 mm). The bulk density of the extrudates was determined by volumetric displacement (g/cc).

The volume of the expanded samples was measured by rapeseed displacement with a 500 mL graduated cylinder. Two hundred grams of randomized samples was measured in each test. The ratio of sample weight to the replaced volume in the cylinder was calculated using the equation of BD (w/v):

Table 1: Experimental design with different levels of oat fiber and oca flour used to obtain collets extruded at different tempering moisture contents.

Samples ID[†]	Oat fiber (%)	Oca flour (%)	Tempering moisture content (%)
F20/O80/M20	20	80	20
F0/O100/M20	0	100	20
F10/O90/M17.5[‡]	10	90	17.5
F20/O80/M13	20	80	13
F0/O100/M13	0	100	13

[†]Identification of the extruded sample. [‡]Nine replicates of the study were made for the middle center point. F = oat fiber; O = oca flour; M = moisture.

$$\mathrm{BD} = \frac{4m}{[(\pi)(d^2)(L)]}, \quad (1)$$

where m is the mass of the extrudate (g), d is the diameter (cm), and L is the length (cm).

2.5. Color Evaluation. The extruded samples were ground into flour using a UDY mill equipped with a US #35 sieve (0.5 mm). The parameters CIE, L^*, a^*, and b^* of each treatment were measured using a Minolta colorimeter (CM-508D, Japan).

2.6. Hardness. The extrudates were cut with a 0.45 mm thick razor blade attached to a TA.XT Plus texture analyzer equipped with a 30 kg load cell (Vienna Court, Lammas Road, Godalming GU7 1YL, UK). The cutting speed and cutting factor were set at 0.5 mm/s and 75% of the extrudate diameter, respectively. Hardness was reported as the highest peak in the force-time curve and was expressed in Newton (N).

2.7. Extraction of Free Phenolic Compounds. Phenolic compounds were extracted with 80% ethanol as extraction solvents. The total phenolic content (TPC) was assessed according to the methodology described by Singleton et al. [17] and Jiménez Martínez et al. [18] using Folin–Ciocalteu reagent. The sample extracts were placed in the dark for 2 h before analysis. The absorbance was measured at 765 nm using a UV/vis spectrophotometer (BOECO S-22, Hamburg, Germany). The TPC was calculated based on a standard curve plotted with gallic acid as a standard. The final results were expressed as milligrams of gallic acid equivalents (GAE) per 100 g dry basis (db).

2.8. Cellular Antioxidant Activity (CAA). The assay for CAA in oca flour and extruded products was performed following the method of Wolfe and Liu [19]. Briefly, Caco-2 (ATCC® HTB-37) cells from passages 5 and 7 were seeded at a density of 6×10^4 in 100 μL of complete growth medium per well on a 96-well microplate in a humidified (5%) CO_2 incubator at 37°C. The wells at the periphery of the microplate were filled with 200 μL of PBS. Twenty-four hours after seeding, the growth medium was removed, and the wells were washed with PBS. The wells were treated in triplicate with 100 μL of solutions containing different concentrations of antioxidant extracts plus 25 μM dichlorofluorescin diacetate (DCFH-DA) dissolved in antioxidant treatment media for 1 h at 37°C. Then, the treatment media were removed, and the wells were washed with 100 μL of phosphate-buffered saline (PBS) to remove extracellular residues. One hundred microliters of 600 μM 2,2′-azobis-2-methylpropionamidine dihydrochloride (APPH) in oxidant treatment medium (HBSS) was applied to all of the cells, and the microplate was immediately placed into a Fluoroskan Ascent FL plate reader (Thermo Labsystems, Franklin, MA) at 37°C. Emission was measured every 5 min for 1 h at 538 nm after excitation at 485 nm. The blank wells contained cells treated with DCFH-DA, HBSS, and antioxidant extracts without APPH, whereas the control wells contained cells treated with DCFH-DA, HBSS, and APPH without antioxidant extracts.

The area under the curve of fluorescence (after subtraction of blank and initial fluorescence values) versus time was integrated to calculate the CAA value for each concentration of the sample extracts as

$$\text{CAA unit} = 1 - \frac{\int \mathrm{SA}}{\int \mathrm{CA}}, \quad (2)$$

where $\int$SA is the integrated area under the curve of sample fluorescence versus time and $\int$CA is the integrated area from the control curve.

2.9. In Vitro Starch Digestibility and Predicted Glycemic Index. The *in vitro* starch hydrolysis rate was measured using hog pancreatic alpha-amylase (A-3176, 10–30 units/mg solid, Sigma Chemical Co.) following the procedure reported by Holm et al. [20]. The amount of reducing sugars released was measured by the dinitrosalicylic acid method (DNS) at 530 nm and a standard curve of maltose. The rate of hydrolysis was expressed as the percentage of digestible starch hydrolyzed at different times. The predicted glycemic index was calculated from the hydrolysis curves using the following empirical formula [21]:

$$\mathrm{pGI} = 39.21 + 0.803\,(H_{90}), \quad r = 0.99,\ p \le 0.05. \quad (3)$$

2.10. Measurement of Integrated Dietary Fiber (IDF). The total content of integrated dietary fiber was quantified in the extruded samples by the following methods AOAC [22] and AACC [23] using a commercial assay kit (K-INTDF) purchased from Megazyme International (Wicklow, Ireland). The assay was conducted according to the manufacturer's instructions. Briefly, the test consisted of treating samples

with protease and the starch-degrading enzymes α-amylase and AMG, followed by two gravimetric filtrations.

2.11. Microstructure and Photographs of Extrudates. The extruded collets were covered with aluminum, immersed in liquid nitrogen for 20 sec, and then split into small pieces. Single small pieces were mounted edge-up using double adhesive carbon tape onto aluminum specimen stubs coated with gold-palladium in a Denton Desk II sputter coating unit (Denton Vacuum, LLC, Moorestown, NJ). A scanning electron microscope (JOEL JSMP 100, Japan) was used to study the internal crumb structure of collets. The scanning electron microscope (SEM) was operated at 5 kV. The extrudates were photographed with a Canon digital camera (SX420 IS) using a 42 × optical zoom.

2.12. Experimental Design and Statistical Analysis. A two-factor design was used to generate the different extrudates. The factors, each with three levels, were tempering moisture and supplementation with oat fiber. A central composite rotatable experimental design was used ($\alpha = 1.682$). The statistical model is as follows:

$$y_i = b_0 + b_1x_1 + b_2x_2 + b_{11}x_1^2 + b_{22}x_2^2 + b_{12}x_1x_2, \quad (4)$$

where y_i is the generic response, x_1 is the tempering moisture percentage, x_2 is the oat fiber percentage, and b_0, b_1, b_2, b_{11}, b_{22}, and b_{12} are the regression coefficients.

The statistical significance of the models was confirmed by analysis of variance, and the influence of the variables was analyzed using response surface graphs with the statistical program Minitab 18.

Data were analyzed with analysis of variance (ANOVA) using a level of confidence of $\alpha = 0.05$, and means were compared with Tukey's test at the same level of significance. The statistical analysis was performed using the statistical program Sigma Stat 12.5.

3. Results and Discussion

3.1. Water Absorption (WAI) and Solubility (WSI) Indexes. In the present study, the highest WAI values were observed in the extruded samples F20/O80/M20, F0/O100/M20, and F10/O90/M17.5 (Table 2), indicating an association with the tempering moisture content of the blends (Table 1). This behavior may be explained by the damage to starch and soluble dietary fiber by the higher temperature and mechanical energy of the extruder, which causes greater exposure of hydrophilic groups, permitting better water penetration into the pellet structure [24]. The collet extrudates were elaborated with higher moisture content and showed a higher water interaction. These same authors found a stronger correlation between MC and WAI than that observed between temperature and WAI. Other authors mentioned that, when the temperature was increased in the presence of moisture, the amylose and amylopectin chains separated and the resulting extended matrix enhanced water absorption [25, 26]. Thus, the application of lower MC in samples yielded lower WAI values, as observed herein.

On the other hand, the investigation of Charunuch et al. [27] showed that the fiber influenced WAI, since higher amounts of fiber in feedstocks reduced the availability of granules starch for gelatinization. In fact, lower WAI values were observed when higher levels of rice bran were included in the extruded samples. A similar behavior was observed herein in the extrudates which contained higher fiber contents. The TDF increased as the oat fiber concentration augmented in the extrudates. In general, this study observed that the increase of oat fiber in the extrudate samples caused a slight decrease in WAI values.

Samples F20/O80/M13 and F0/O100/M13, extruded with feedstocks containing 13% moisture, showed lower WAI values.

The water solubility index (WSI) showed an inverse pattern compared with WAI; a lower MC corresponded to higher WSI values. Delgado-Nieblas et al. [24] reported a similar behavior: When the temperature increased to 141°C and the MC decreased, the WSI increased. They explained this pattern by suggesting that the increase in temperature and the decrease in MC may have caused an increase in the degradation of starch molecules by the higher shear and friction inside the extruder, resulting in high mechanical damage. The WSI, which is often used as an indicator of molecular degradation, measures the degree of starch fragmentation during thermoplastic extrusion [28]. In the present study, the content of oat fiber and moisture had significant effects on WAI and WSI (Table 3).

3.2. Color Properties of Extrudates. The color parameters such as lightness (L^*), redness (a^*), and yellowness (b^*) of the extrudates are shown in Table 2. According to the values of these parameters, the moisture and oat fiber content used to elaborate the extrudates had a significant statistical effect ($\alpha = 0.005$). This pattern can be observed in Figure 1 (see photographs of the extruded products). Samples F0/O100/M20 and F0/O100/M13 are equal in oca flour content, but they were elaborated with different moisture contents (MCs), which affected the color values. The extrudate samples elaborated with higher oat fiber content (ID: F20/O100/M20 and F20/O80/M13) also showed a significant statistical effect ($\alpha = 0.005$) on the color parameters. However, Table 3 shows that the moisture content has more influence on the color parameter than the oat fiber content.

WAI = water absorption index; WSI = water solubility index; BD = bulk density; EI = expansion index; H = hardness; TDF = total dietary fiber; CAA = cellular activity antioxidant; HI = hydrolysis index; pGI = predicted glycemic index; M = moisture; F = oat fiber.

3.3. Physicochemical Test of Extruded Samples. Figure 2 shows the physicomechanical properties of the extruded collets. Bulk density (BD) is a parameter associated with puffing. In general, the extruded samples showed an inverse relationship between the radial expansion index (EI) and BD. Figure 2 depicts that extrudates with higher BD values had the lowest EI values and vice versa. Delgado-Nieblas et al. [24] studied the comparative effect of extrusion

Table 2: Water solubility index, water absorption index, and color results of different mixtures of extruded collets from oca flour mixed with oat fiber.

Samples ID	WAI	WSI	L^*	a^*	b^*
F20/O80/M20	3.8 ± 0.23b	33.4 ± 2.5**a	34.20 ± 2.85a	9.29 ± 0.85a	13.11 ± 2.0a
F0/O100/M20	4.0 ± 0.44b	32.3 ± 2.5***a	10.46 ± 0.54b	16.2 ± 1.32b	17.52 ± 0.54 b
F10/O90/M17.5†	4.2 ± 0.51b	39.1 ± 4.7a	39.34 ± 1.67c	6.21 ± 0.18c	7.8 ± 0.50c
F20/O80/M13	2.8 ± 0.15a	44.5 ± 7.1b	42.96 ± 1.48d	8.93 ± 0.07d	15.25 ± 0.31a
F0/O100/M13	2.7 ± 0.14a	49.1 ± 1.4b	42.66 ± 0.24cd	6.29 ± 0.10c	7.41 ± 0.16c

**Average of 5 repetitions ± standard deviation. ***Means with different letters within column are significantly different ($p < 0.05$). †Nine replicates of the study were made for the middle center point. For sample IDs, refer to Table 1.

Table 3: Contribution of each factor (%), according to ANOVA, to the physicomechanical properties (TDF, CAA, HI, and pGI) of extruded collets from oca flour mixed with oat fiber†.

Factors	WAA	WSI	L^*	A^*	B^*	BD	EI	H	TDF	CAA	HI	pGI
F	0.04	18.97*	27.48*	13.71*	0.10	4.03*	18.90*	3.10*	69.42*	35.66*	67.29*	65.04*
M	9.16	8.42*	52.79*	32.05*	14.19*	86.62*	50.14*	73.10*	6.04	1.79	7.40*	13.08*
F*F	25.90*	43.78*	19.62*	44.34*	54.70*	20.94*	0.007	34.34*	0.001	24.03*	12.59*	15.46*
F*M	19.29	27.84*	17.29*	27.64*	33.43*	1.71*	12.42*	5.41*	5.32	2.67	1.17*	4.22*

*The constants with asterisk showed significant effects when analyzed with the experimental design implemented. †Factor contributions calculated by dividing each factor's sum of squares by the total sum of squares and multiplying by 100%.

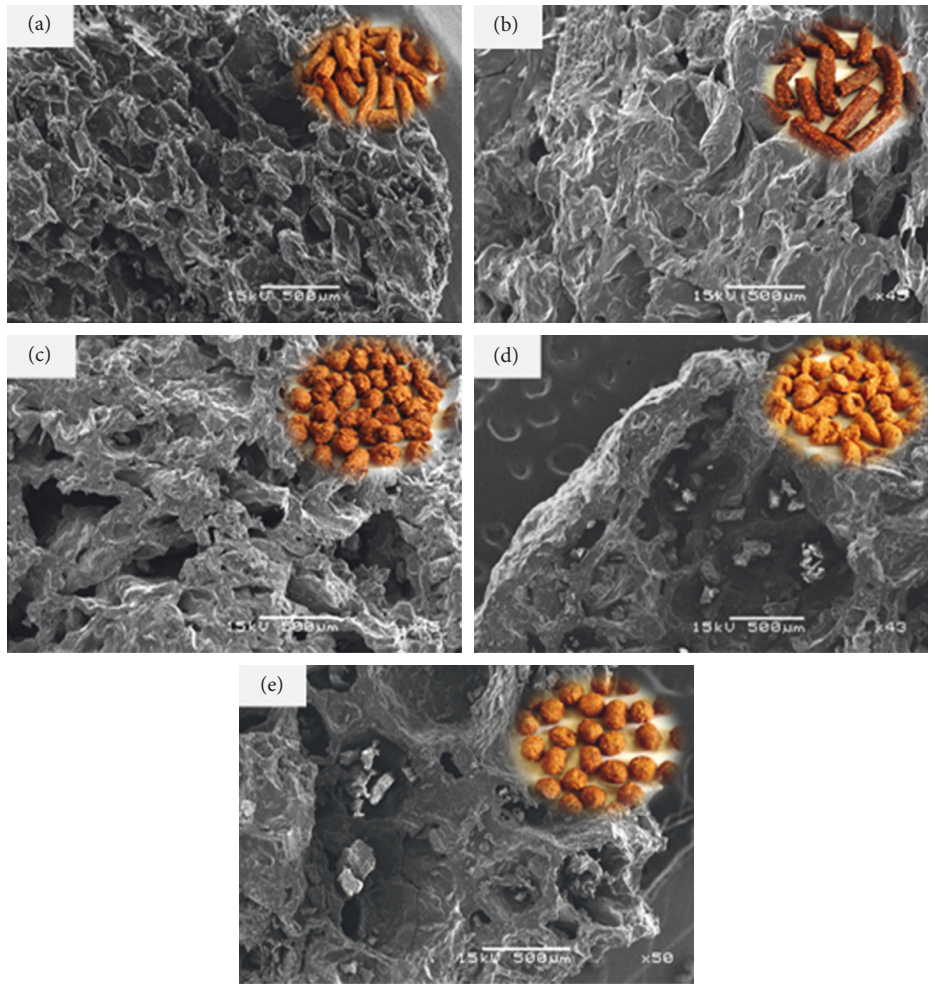


Figure 1: SEM images of the extruded breakfast products made from oca flour. Sample ID: (a) F20/O80/M20; (b) F0/O100/M20; (c) F10/O90/M17.5; (d) F20/O80/M13; and (e) F0/O100/M13. For sample IDs, refer to Table 1.

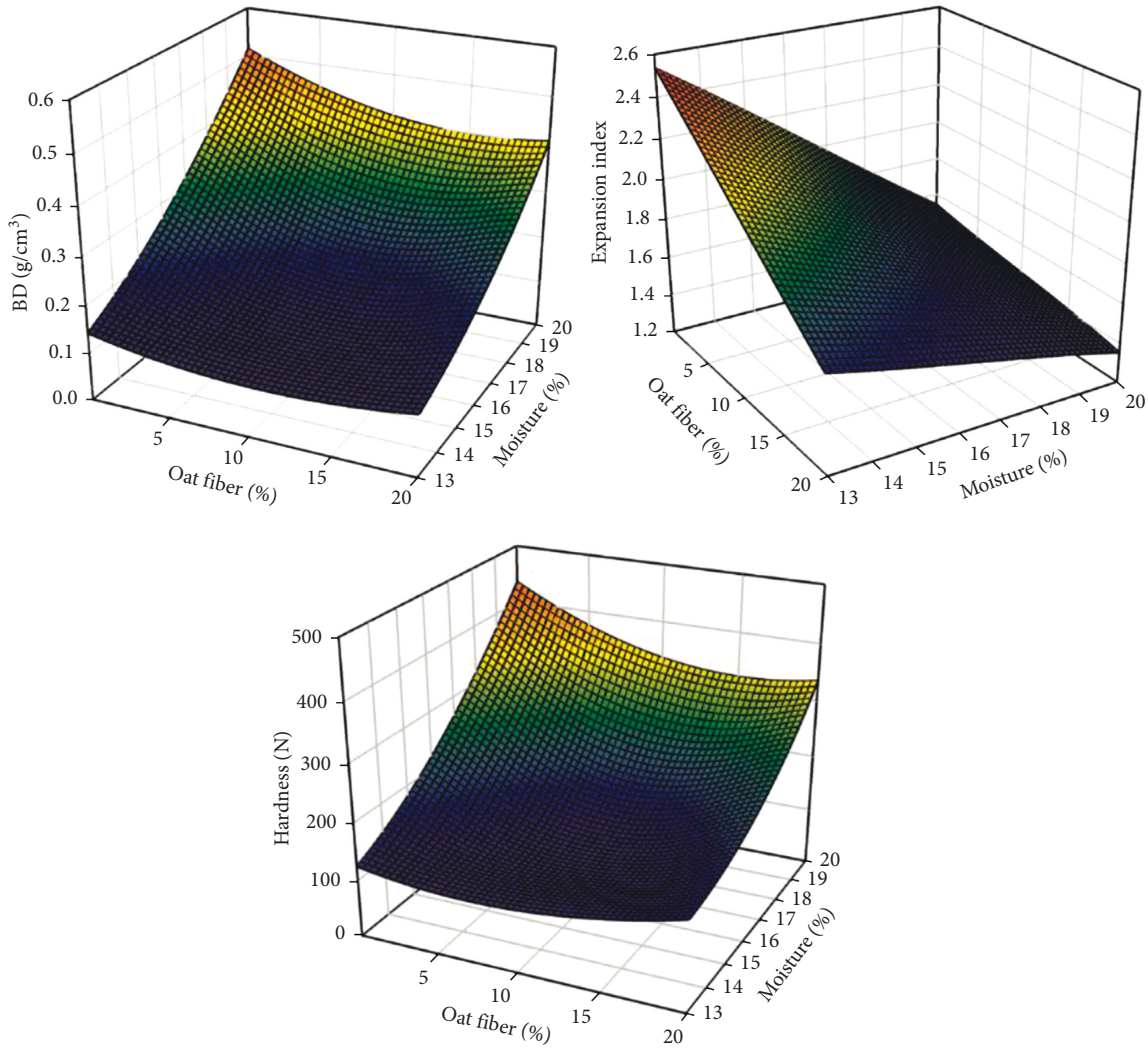


Figure 2: Effects of supplementation with different levels of oat fiber and tempering moisture content (%) on bulk density (BD "g/cm^3"), expansion index, and hardness (*N*) of the collets made from oca flour.

temperature and moisture content (MC) on the BD values of snack foods, reporting an increase in BD values when MC increased. Using regression analysis, Chulaluck et al. [29] analyzed the relationship between vegetable powder and MC in the extrudates, finding that both variables influenced both BD and EI values. The same pattern was observed herein, where the addition of different levels of oat fiber to the feedstock significantly affected the structure and texture of the extrudates. Higher levels of oat fiber limited the expansion rate because the high fiber acts as a filler material and dilutes the starch mainly responsible for the expansion rate. In fact, the higher fiber content increased and decreased the BD and EI values, respectively. The moisture content of the starch-based material reflects the high dependence of bulk density values and expansion index [29].

Textural properties such as hardness (*H*) are important parameters in the extruded samples because they are associated with consumer acceptance. It was observed that an increase in MC resulted in extruded products with a higher hardness compared to the extrudates obtained with high oat fiber content. This pattern has been reported in several studies of second-generation extruded snacks where the hardness is the average force required for a probe to penetrate the extrudates. Besides that, the hardness of the extrudates increased as the feed moisture content increased [30–33].

The hardness of the expanded extrudates is associated with the expansion and cell structure of the food products. In the present study, the increase in hardness could be explained by the increase in MC during the extrusion process, which reduced the degree of starch gelatinization and in turn, also diminished the expansion index of the extrudates. Similar behavior was reported by Ajita and Jha [34], who mentioned that an increase in feed moisture during the extrusion process may reduce the elasticity of dough through plasticization of the melt, resulting in reduced specific mechanical energy and gelatinization, which decreased expansion and increased extrudate density (Figure 2) in this study. Furthermore, the higher levels of oat fiber in the feedstock increased cell wall thickness and decreased porosity, which clearly generated harder collets. This

pattern was observed microscopically (Figure 1). The factor that contributed most to the hardness properties was the MC used during the extrusion process (Table 3).

3.4. Total Dietary Fiber and Cellular Antioxidant Activity. Figure 3 shows the effect of oat fiber and tempering moisture content on the total dietary fiber (TDF) and cellular antioxidant activity (CAA) of oca flour-based extrudates. An increase in both factors (oat fiber and MC) caused an increase in TDF values. Delgado-Nieblas et al. [24] reported that the use of higher extrusion temperatures increased the content of soluble dietary fiber and decreased the amount of insoluble dietary fiber. Possible explanations for this relevant effect are the disruption of cell walls, which releases soluble dietary components and hydrolyzed insoluble polysaccharides, and the production of resistant starch type 3 formed during harsh extrusion conditions. Resistant starch is mainly assayed as soluble dietary fiber [35].

Theander and Westerlund [36] reported the same behavior observed in the present study and attributed it to various processes: (1) the formation, by external transglycosidation, of glycans resistant to enzymatic action; (2) the quantification of lignin polymers formed during the Maillard reaction; and (3) the formation of resistant starch by retrogradation. Thus, newly formed indigestible glycans may have contributed to the increased TDF. The statistical analysis (ANOVA) ($\alpha = 0.005$) indicated that fiber content had more influence on TDF values than tempering moisture content in the extrudate samples made from oca flour (Table 3).

The cellular antioxidant activity (CAA) assays of the extruded collets showed a slight reduction in the CAA values (2 units) between oca flour before extrusion and the extrudate samples (Figure 3). Similar behavior was reported by Nayak et al. [10], who found that CAA in extrudates may increase due to three processes: (1) disruption of plant cell walls providing better extractability; (2) breaking of chemical bonds of higher-molecular-weight polyphenols and formation of soluble low-molecular-weight polyphenol compounds; and (3) interconversion of flavonoids in different forms.

Additionally, it was observed that levels of oat fiber greater than 10% caused a drastic reduction in the CAA values of extrudates. This behavior may be associated with the comparatively higher antioxidant capacity of purple oca compared to oat fiber [12]. A similar trend was reported in the expanded extrudates made from purple potatoes and yellow peas [37]. Furthermore, the high temperature used during the extrusion of collets likely promoted the Maillard reaction and broke the bonds of complex polyphenols, inducing the formation of browning compounds that may have affected CAA [38]. Higher tempering moisture contents caused a slight increase in the CAA. A similar behavior was reported by Nayak et al. [37] and Escalante-Aburto et al. [39] in extruded snacks made from purple potatoes and blue corn. The explanation for this slight increase could be that water in the mixture reduced the internal temperature and shear, yielding extrudates with reduced loss of CAA. However, Table 3 shows that the content of oat fiber had a significant influence on CAA ($p < 0.05$).

3.5. Hydrolysis Index (HI) and Predicted Glycemic Index (pGI). The hydrolysis index (HI) was calculated from the rate of starch hydrolysis and the corresponding predicted glycemic index (pGI), as shown in Figure 4. Both indexes showed a similar behavior, decreasing when the concentration of oat fiber increased in the extrudates. It is well known that the contents of fiber, fat, and protein have a drastic effect on the release of glucose. Jiang et al. [40] and Naguleswaran et al. [41] reported that the relative crystallinity, amylose content, botanical source, and moisture content of starch granules also influence starch hydrolysis and glycemic indexes. Nayak et al. [4] mention that the conditions of the extrusion process, including temperature, moisture (starch-to-water ratio), and screw speed, among others, cause changes in the physical and chemical structure of starch and consequently, the pGI of the final extruded products. Table 3 shows that HI and pGI were highly dependent on fiber, rather than the tempering moisture content, and that there was a quadratic correlation between fiber-fiber and fiber-tempering moisture. The reduction of HI and pGI could be due to the increased MC used in the extrusion; as mentioned by some authors, an increase in feed moisture during extrusion may change the amylopectin molecular structure of the starch-base material, thereby reducing the elasticity of dough, resulting in reduced specific mechanical energy and reduced gelatinization [34, 42]. A reduction in starch gelatinization caused a reduction in HI and pGI in the samples.

Previous studies have also shown that a diet with low GI and high contents of resistant starch helps reduce insulin resistance, adjusts blood glucose levels, improves lipid metabolism, and prevents cardiovascular and cerebrovascular diseases [43]. The glycemic index is thus related to the nutritional quality of food, and a product with a low glycemic index is preferable not only for individuals with diabetes but also for healthy populations [44].

3.6. Microstructure and Photographs of the Extruded Products. Scanning electron microscopy (SEM) revealed the internal structures of the products extruded under different conditions (Figure 1). The microstructure shows that the tempering moisture content plays an important role in the expansion of the collets. Samples F20/O80/M13 and F0/O100/M13, which were extruded at relatively low tempering moisture contents (13%), had larger cells with lower BD and hardness and higher EI values. Jacques-Fajardo et al. [33] reported that in the extruded samples made from corn, peas, and oat bran, the samples with lower tempering moisture content also had higher EI and larger cells. Bisharat et al. [45] and Silva et al. [8] reported that extrudate expansion results from the internal pressure of water that remains inside the matrix during gelatinization and is released when the product exits the extruder die, causing expansion, larger cells, and thinner cell walls, which in turn reduces the hardness of the extrudates.

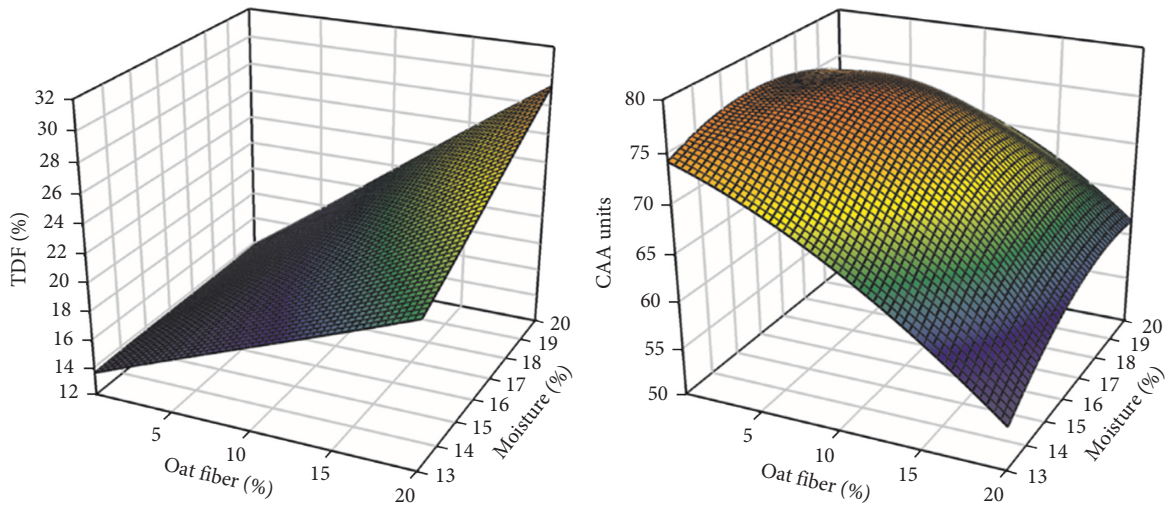


Figure 3: Effects of supplementation with different levels of oat fiber and tempering moisture contents (%) on total dietary fiber (TDF) and cellular antioxidant activity (CAA) of the collets made from oca flour.

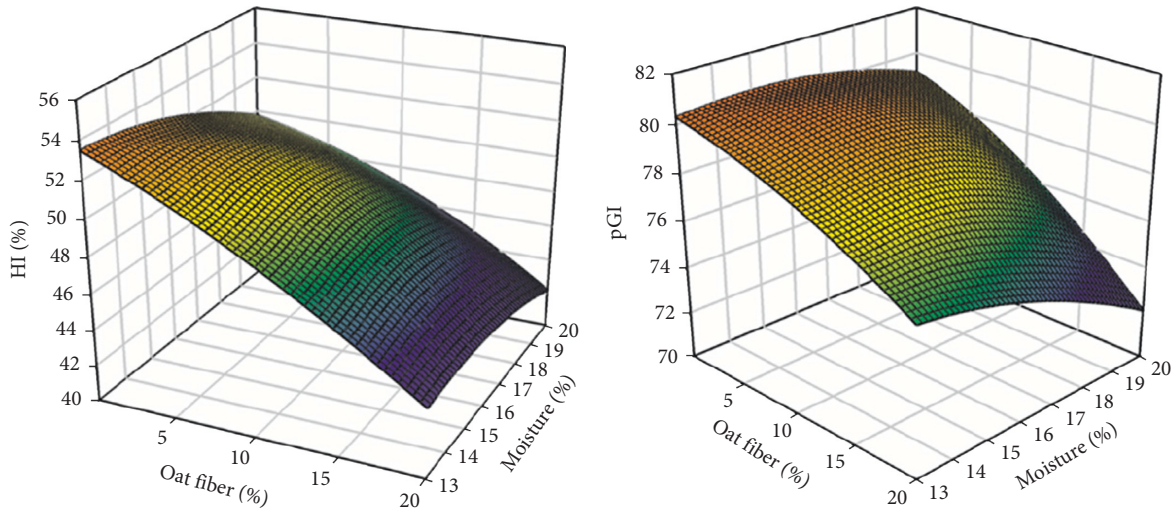


Figure 4: Effects of supplementation with different levels of oat fiber and tempering moisture content (%) on the starch hydrolysis index (HI) and the predicted glycemic index (pGI) of the collets made from oca flour.

Photographs of the extruded samples are inset with the micrographs. They show that a lower tempering moisture corresponded to more homogeneous extrudates in round forms.

4. Conclusion

Regression analyses were used to evaluate the effect of oat fiber and moisture content on CAA HI, pGI, and the physicomechanical properties of extrudates and to verify the results. The tempering moisture content used during the extrusion process had the greatest influence on the extruded samples. The inclusion of oca flour in the elaboration of extruded puffs was a good option due to its high CAA capacity. Furthermore, the use of oat fiber in the mixture slowed starch digestion, allowing for a controlled liberation of sugar into the bloodstream. The extruded materials studied herein can be considered functional foods because they can provide health benefits and prevent chronic diseases.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that no conflicts of interest exist related to this publication.

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