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Production of Extrudate Food with Mango By-Products (*Mangifera indica*): Analysis of Physical, Chemical, and Sensorial Properties

Esther Alicia Medina-Rendon [1], Guadalupe María Guatemala-Morales [1,*], Eduardo Padilla-Camberos [2], Rosa Isela Corona-González [3], Enrique Arriola-Guevara [3] and Jorge Alberto García-Fajardo [4,*]

1 Tecnología Alimentaria, Centro de Investigación y Asistencia en Tecnología y Diseño del Estado de Jalisco, A.C., Normalistas 800, Guadalajara C.P. 44270, Jalisco, Mexico; esmedina@ciatej.edu.mx
2 Biotecnología Médica y Farmacéutica, Centro de Investigación y Asistencia en Tecnología y Diseño del Estado de Jalisco, A.C., Normalistas 800, Guadalajara C.P. 44270, Jalisco, Mexico; epadilla@ciatej.mx
3 Departamento de Ingeniería Química, Centro Universitario de Ciencias Exactas e Ingenierías, Universidad de Guadalajara, Blvd. Marcelino García Barragán #1421, esq. Calzada Olímpica, Guadalajara C.P 44430, Jalisco, Mexico; rosa.corona@academicos.udg.mx (R.I.C.-G.); enrique.arriola@academicos.udg.mx (E.A.-G.)
4 Subsede Noreste, Centro de Investigación y Asistencia en Tecnología y Diseño del Estado de Jalisco, A.C., Parque de Investigación e Innovación Tecnológica (PIIT), Apodaca C.P. 66629, Nuevo León, Mexico
* Correspondence: gguatemala@ciatej.mx (G.M.G.-M.); jgarcia@ciatej.mx (J.A.G.-F.); Tel.: +52-81-8215-5200 (ext. 3011) (J.A.G.-F.)

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Abstract: The novelty of this work is the use of two mango by-products, mango peel and kernel, to obtain an extruded food. As well as the development of this food through a design of mixtures, we conducted sensorial analysis of the food through a hedonic test, in order not only to develop an extruded food with mango by-products, but also to develop a food that will be accepted by the consumer. A simple lattice mixture design was carried out with 14 mixtures, where the components were white corn flour (WCF), mango peel flour (MPF) and mango kernel flour (MKF), both from the Tommy Atkins mango variety. Physical and chemical properties such as the expansion index (EI), hardness, water absorption index (WAI), water solubility index (WSI), total phenols, DPPH and ABTS were evaluated. An optimization region was found that included 3 design points. Mixtures 1, 6 and 12 were evaluated using a nine-point hedonic scale to determine the acceptability of the product. Appearance, taste, and texture of the extrudates was evaluated. The extrudate with the best overall acceptability and the optimum physical and chemical properties contained 58.33% white corn flour, 33.33% mango peel flour and 8.33% mango kernel flour.

Keywords: by-products mango; mango peel flour; mango kernel flour; food extrudate; mixture design; hedonic test; physical properties; chemical properties

1. Introduction

Mango (*Mangifera indica*) is the most widely available commercial fruit in countries of the tropical region. World production in 2019 was 55.9 million tons [1]. The largest producers are India, China, Thailand, Indonesia, and Pakistan. México is the world's sixth largest producer, producing 2,089,041 tons [2]. Obtaining an industrial agricultural product implies waste or by-product generation that represents an environmental problem. Due to inadequate management, by-products are dumped in landfills and lead to the proliferation of microorganisms. By-products are generated in large volumes at a national level, and only minimal parts are reused in the production of low value-added animal feed. Mango by-products (peel, seed, and the pulp attached to both) constitute 35–60% of the total weight of the fruit. Mango industrialization is a form of decreasing losses in high season and maximizing its exploitation [3].

Mango peel and seed extracts also have potential as an additive, by influencing the sensory and physicochemical characteristics of foods, which has been proven by their addition to products such as shrimp, yogurt, and cookies [4]. One of the most promising strategies for reusing mango by-products is to convert them into powders. Mango by-product powders have been incorporated into bakery products, pastas, and jellies, increasing their content of fiber, phenolic compounds, and carotenoids, and improving their antioxidant activity and glycemic index [5].

Extrusion is applied in the food processing industry to produce extruded foods; it is an economical technology for incorporating food processing by-products. Extruders can modify starches, proteins, and other food materials to produce a wide variety of new food products. Extruded products have a lower moisture content, longer shelf life and are microbiologically safe. The versatility, cost, productivity, product quality, environment friendliness, energy efficiency and the production of new foods are advantages of this technology. On the other hand, drawbacks of the extrusion process are deterioration of proteins and reduced sugars due the use of high temperature treatments, that affect nutritional characteristics. The elevated temperatures and low moisture conditions used in the extrusion process can lead to chemical reactions such as non-enzymatic browning and caramelization. Excessive heat also causes product color to fade due to expansion [6]. Extruded products such as direct-expanded products, breakfast cereals, and pasta have been developed by researchers using agricultural by-products. The different by-products have a wide range of characteristics in terms of chemical composition and functional properties, each affecting the final products in extrusion processing. For the practical applications of these by-products in extrusion, it is crucial to understand their impacts on the qualities of raw material blends and extruded products [7].

Full development of the extrusion process requires a study of the function and operation of extruders, combined with the characterization of the structural, physical, and rheological property changes in the food materials [8]. Extruded cereal-based snacks are popular products, however, many snacks on the market are currently high in salt, fat and sugar, with an overall low nutritional value [9]. Incorporation of mango peel powders in food could help to enhance the nutritional, physicochemical and sensory characteristics of food products [4,5]. Thus, this is where a significant research opportunity is present.

The aim of this work is to explore the addition of two mango by-products as ingredients (mango peel and kernel) to obtain an extruded food through a mixture design, the acceptance of the food by consumers will also be verified through a hedonic test. The results of this study will form the basis for future work on the reduction of mango by-products and healthy foods.

2. Materials and Methods

2.1. Materials

White Corn (*Zea mays*) and the mango (*Mangifera indica*) variety Tommy Atkins were purchased at a food market in Guadalajara, Jalisco. Mangos with a similar degree of maturity were determined by color, firmness, total soluble solids, and pH. Color attributes were measured using a Hunter Lab Mini Scan EZ model 4500L colorimeter (Reston, VA, USA). Firmness was measured with a Stable Micro Systems texturometer model TA-XT Plus (Godalming, United Kingdom) at a speed of 1 mm/s with 1 cm of penetration. Total soluble solids were measured with an ATAGO Model PAL-α digital refractometer (Bellevue, WA, USA). pH was measured with an Oakton model pH 2700 Benchtop Meter (Vernon Hills, IL, USA) digital potentiometer. White corn (*Zea mays*) was milled to obtain an average particle size of 0.60 mm in a Pulvex Maren 1.5HP disk mill (Iztacalco, CMX, México) [10]. Analytical grade chemicals: methanol; acetone; Folin-Ciocalteu reagent; Gallic acid (3,4,5-Trihydroxybenzoic acid); 2,2-Diphenyl-1-picrylhydrazyl (DPPH); 2,2′-Azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt (ABTS); (±)-6-Hydroxy-2,5,7,8-tetramethylchromane-2-caroxylic acid (Trolox); potassium Persulfate ($K_2S_2O_8$) and sodium carbonate (Na_2CO_3) were purchased from Sigma-Aldrich (St. Louis, MO, USA).

2.2. Production of Mango Peel Flour and Kernel Mango Flour

All mangos were washed with water and cleaned with a sponge and commercial disinfectant soap. Then, disinfection was performed by immersion in a 0.5% solution of Killerbac (Zapopan, JAL, Mexico) for 10 min. Mangos were cut manually to separate the pulp, peel, and seed. The kernel was extracted from the inside of the mango seed. The mango peels and kernel were sliced to obtain a uniform size using a Hobart model FP100 food processor (Troy, OH, USA). The mango peel and kernel were dried in a DESPATCH model F-195 convection oven (Minneapolis, MN, USA) at a constant temperature of 60 °C [6]. The mango peel was milled to an average particle size of 0.50 mm using an Oster® 16-speed glass beaker model 6859-126-000 (Acuña, COA, México). The mango kernel was milled to an average particle size of 0.40 mm in an International Food grade stainless steel industrial blender, model IT-LI5 (Nezahualcoyotl, MEX, México). The flours were kept at room temperature in sealed polyethylene bags for later use [11,12].

Chemical Analysis

Chemical analysis of corn flour and mango peel and kernel flours were determined according to Mexican regulations. Moisture (NMX-F-083-1986) [13]; protein (NMX-F-608-NORMEX-2011) [14]; ashes (NMX-F-607-NORMEX-2013) [15]; fats (ethereal extract) (NOM-086-SSA1-1994) (Normative Appendix C, Number 1 [16]; crude fiber (NMX-F-613-NORMEX-2003) [17]; carbohydrates, determination by difference (Method 986.25) A.O.A.C. Volume l. 1990 [18].

2.3. Extrusion Process

White corn flour (WCF), mango peel flour (MPF) and mango kernel flour (MKF) according to points of mixture design (Table 1) were mixed using a laboratory mixer Kitchen Aid Professional Series 600 Model KP26M1XER (St. Joseph, MI, USA) at speed 4, for 10 min, adjusted to different moistures, placed into plastic bags, and maintained over-night (12–14 h) before processing. In each treatment, 500 g of sample was used [19]. The different blends WCF, MPF, MKF were extruded using a Brabender single-screw extruder Intelli-Torque Plasti-Corder (South Hackensack, NJ, USA) with the following characteristics: pressure and temperature sensor; three heating zones; 20:1 L/D; screw with 3:1 compression ratio; screw diameter of 19.05 mm and a 3 mm diameter × 20 mm long circular die. The extruded samples were dried at 60 °C in a forced convection oven RedLINE by Binder model RF115 (Tuttlingen, BW, Germany) until moisture was reduced to approximately 5%. Dried samples were stored in polyethylene bags at room temperature and used for further analysis [20].

Table 1. Composition of extrudate food with mango by-products in a simplex lattice mixture design.

Point	Mixtures	WCF [a] (%)	MPF [b] (%)	MKF [c] (%)
A	1	75.00	25.00	0.00
B	2	58.33	41.67	0.00
D	3	58.33	25.00	16.67
E	4	41.67	58.33	0.00
F	5	41.67	41.67	16.67
G	6	41.67	25.00	33.33
J	7	25.00	75.00	0.00
K	8	25.00	58.33	16.67
L	9	25.00	41.67	33.33
M	10	25.00	25.00	50.00
F	11	41.67	41.67	16.67
C	12	58.33	33.33	8.33
H	13	33.33	58.33	8.33
I	14	33.33	33.33	33.33

[a] WCF: White Corn Flour, [b] MPF: Mango Peel Flour, [c] MKF: Mango Kernel Flour.

2.4. Physical Properties

2.4.1. Expansion Index (EI)

The diameter (mm) of 10 randomly selected extruded samples was measured. The expansion rate was calculated by dividing the diameter of the extrudate by the diameter of the orifice of the exit die of the extruder [8].

2.4.2. Hardness

The texture attribute was determined by measuring the hardness of the extrudates using a Stable Micro System texture analyzer, model TA-XT Plus (Godalming, SY, UK), fitted with a 2 mm radius cylinder probe in compression mode. The samples were punctured by the probe at 10 mm of distance, at a speed of 5 mm/min and 20% penetration. Hardness in Newtons (N) was determined by measuring the maximum force required to break the extruded samples. Ten randomly collected samples of each extrudate were measured and averaged [21].

2.4.3. Water Absorption Index (WAI) and Water Solubility Index (WSI)

We followed the method in Anderson et al. [22]. A milled sample of 2.5 g was mixed with 25 mL of distilled water in a centrifuge tube, which was shaken in a Genie Scientific Industries model SI-1100 rotary-shake (Bohemia, NY, USA) for 30 min at 25 °C. The suspension was centrifuged in a Luzeren Universal Centrifuge model TDL-40B (Tlajomulco de Zúñiga, JAL, Mexico) run at 2770× g, 10 min, 25 °C. Supernatant liquor from each tube was transferred into previously weighed aluminum trays to be dried at 80 °C for 24 h in a forced convection oven RedLINE by Binder model RF115 (Tuttlingen, BW, Germany). WAI was expressed as the weight of the wet sample per gram of sample. WSI was expressed as the percentage of dry solids in the supernatant per gram of original sample [22].

2.5. Chemical Properties

2.5.1. Preparation of Sample Extracts

These extracts were used for total polyphenol, DPPH and ABTS analysis. The extraction method was adapted by Siddiq et al. [23]; 1 g of milled sample was mixed with 20 mL of methanol (50%) and stirred at room temperature for 1 h in a Genie Scientific Industries model SI-1100 Roto-shake (Bohemia, NY, USA). The mixtures were centrifuged at 3000× g for 15 min, at 4 °C in a Labogene model 1248R Centrifuge (Lynge, ALL, Denmark). The residue was extracted with additional 20 mL acetone (70%) as described above. Both supernatants were combined and used for the determination of total phenolic and antioxidant activity.

2.5.2. Total Polyphenol Determination

The quantification of total polyphenols was carried out using the Folin–Ciocalteu method proposed by Benvenuti et al. [24]. The extracts (30 µL) were mixed with 150 µL of Folin–Ciocalteu reagent (1:10), later 120 µL of 20% (w/v) Na_2CO_3 (sodium carbonate) was added in a 96-well microplate and left to react for 60 min in the dark. The absorbance at 760 nm was read in a ThermoFisher Scientific model Multiskan GO micro-plate spectrophotometer (Waltham, MA, USA). The blank used was methanol. Total phenol content was expressed as mg gallic acid equivalents (GAE)/100 g sample.

2.5.3. Determination of Antioxidant Activity

The antioxidant activity of the extracts was determined by two methods: DPPH (free radical scavenging) assays and ABTS.

DPPH (2,2-diphenyl-1-picrylhydrazyl) radical was measured according to a method reported by Gunec et al. [25] with some modifications. The sample extracts (20 µL) were mixed with 200 µL of an methanolic DPPH solution (500 µmol) in a 96-microwell plate. Methanol was used for blank. The plate was left to stand in the dark for 30 min. The absorbance was measured spectrophotometrically at 515 nm by microplate reader model

Multiskan Go, Thermo Fisher (Waltham, MA, USA). The results are expressed as mg Trolox Equivalents/g sample.

The ABTS assay was carried out according to a method reported by Cam et al. [26] with slight modifications. A solution of 7 mM ABTS and 2.5 mM potassium persulfate were mixed and maintain at room temperature in the dark for 16 h before use it. The solution was diluted in methanol until reaching an absorbance of 0.7 ± 0.02 at 734 nm. The sample extracts (20 µL) were mixed with 200 µL of an methanolic DPPH solution (500 µmol) in a 96-microwell plate. Methanol was used for blank. Methanol was used for blank. The plate was left to stand in the dark for 6 min. The absorbance was measured spectrophotometrically at 734 nm by microplate reader model Multiskan Go, Thermo Fisher (Waltham, MA, USA). The results are expressed as mg Trolox Equivalents/g sample.

2.6. Sensory Evaluation of Extrudates

Sensory evaluation was carried out with a consumer test with one hundred untrained panelists. Based on the optimization of mixture design response variables (EI, Hardness, WAI, WSI, Total Polyphenol, ABTS, DPPH), three extrudates were selected. A nine-point hedonic scale (from 1 = extremely dislike to 9 = extremely like) was used to evaluate the preference of the products. The attributes examined were appearance, taste, and texture of the extruded products. A Tukey multiple range test was used to differentiate the sensory data [20]. Analysis of variance (ANOVA) was performed to determine the differences between treatment means, according to Tukey's test ($p < 0.05$).

2.7. Experimental Design and Statistical Analysis

A simplex lattice mixture design with 14 mixtures (Table 1 and Figure 1) was established and analyzed with WCF (25–75%), MPF (25–75%) and WKF (0–50%). The limits of WCF, MPF and MKF were determined according to previous studies (data not shown). Figure 1 shows the 14 points of the simplex lattice mixture design. Based on the results of Rodríguez-Miranda et al. [27] and preliminary tests, extrusion conditions were a feed moisture content of 17%, a screw speed of 100 rpm, a feed flow of 20 g/min and a die temperature of 120 °C. Response variables were EI, Hardness, WAI, WSI, Total Phenols, DPPH and ABTS. Data were analyzed with analysis of variance (ANOVA) for each response. A value of $p < 0.05$ was considered significant. All analyses were performed in triplicate and data were reported as means ± SD, using Statgraphics Centurion XV (Statgraphics Technologies, Inc., The Plains, VA, USA) [28].

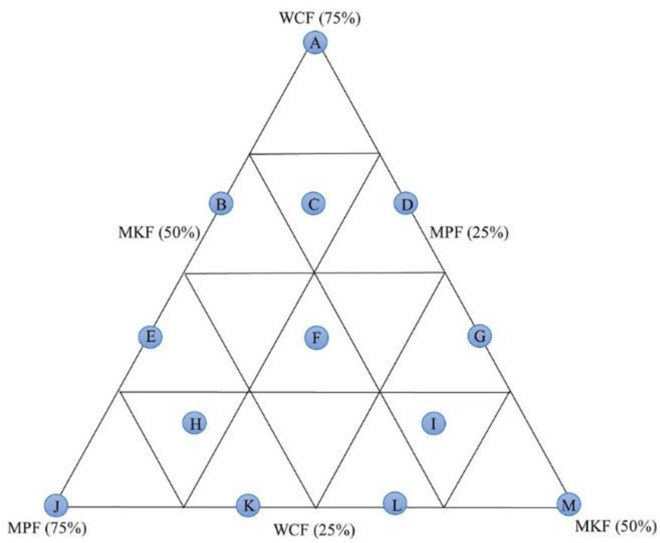

Figure 1. Point of Design Simplex-lattice. White Corn Flour (WCF), Mango Peel Flour (MPF) and Mango Kernel Flour (MKF).

Response values were fitted using linear, quadratic, and special cubic models (Equations (1)–(3)):

$$Y = \lambda_1 X_1 + \lambda_2 X_2 + \lambda_3 X_3 \ (linear) \quad (1)$$

$$Y = \lambda_1 X_1 + \lambda_2 X_2 + \lambda_3 X_3 + \lambda_1\lambda_2 X_1 X_2 + \lambda_1\lambda_3 X_1 X_3 + \lambda_2\lambda_3 X_2 X_3 \ (quadratic) \quad (2)$$

$$Y = \lambda_1 X_1 + \lambda_2 X_2 + \lambda_3 X_3 + \lambda_1\lambda_2 X_1 X_2 + \lambda_1\lambda_3 X_1 X_3 + \lambda_2\lambda_3 X_2 X_3 + \lambda_1\lambda_2\lambda_3 X_1 X_2 X_3 (cubic) \quad (3)$$

where Y is the predictive dependent variable physical properties (EI, Hardness, WAI, WSI) and chemical properties (Total Polyphenol, DPPH, ABTS). λ is the constant coefficient for linear and non-linear terms, and X is proportion of real components [29].

3. Results and Discussion

3.1. Production of Mango Peel and Kernel Flour

3.1.1. Characterization of Mango Fruit

The degree of mango maturity was L* = 29.60 ± 3.26, a* = 6.84 ± 2.78, b* = 30.28 ± 7.47; 10.2 ± 0.81 °Brix; 4.44 ± 0.22 Kgf; pH = 3 ± 0.65. The initial moisture was 78.50% and 55.60% for the mango peel and kernel, respectively. The drying time of the mango by-products was 22 h for the mango peel and 11 h for the mango kernel. The final moisture was 7.99% for the peel and 6.86% for the kernel. Compared with other drying methodologies, Chaparro Acuña et al. [30] extracted the kernel and dried it at 40 °C for 24 h; this was more than twice the time used in our study, because a lower temperature was used.

3.1.2. Characterization of Flours

Table 2 shows the characterization of flours and suggest that we could take advantage of the protein in mango kernel flour (MKF) and white corn flour (WCF) and the amount of fiber in the mango peel flour (MPF), which, if added to a product, could provide a source of protein and fiber.

Table 2. Bromatological analysis of mango peel and kernel flours.

Analysis	WCF [a]	MPF [b]	MKF [c]
Moisture (%)	11.51	7.99	6.86
Protein (%)	7.57	2.88	6.31
Ash (%)	1.24	1.74	1.97
Fat (%)	2.22	1.51	9.94
Total carbohydrates (%)	75.89	74.65	72.37
Fiber (%)	1.57	11.23	2.55

[a] White Corn Flour, [b] Mango Peel Flour and [c] Mango Kernel Flour.

Razo Avila, [31] characterized the mango peel and obtained 10.35% fiber, 2.24% fat, 2.82% protein, a moisture of 5.24% and 4.23% ash. The amount of fat in the mango kernel is 9.94%, which could present issues since fat values above 5% are not recommended in the extrusion process. Ramírez García et al. [32] found similar values of fat at 9.5%, 2.21% ash, 0.14% fiber, 2.2% protein, 85.95% carbohydrate and a moisture content of 4.15%. Chaparro Acuña et al. [30] obtained a value of 10.70% crude fat and 6.39% crude protein; these values are relatively close to those obtained from the bromatological analysis. The differences found in the proximal analysis may be caused by the difference in the variety of the mango, the climate, or the state of maturity.

3.2. Physical Properties

3.2.1. Expansion Index (EI)

Processing conditions and major ingredients could significantly influence the degree of expansion, since they dictate the type and extent of physical and chemical modifications that take place during extrusion which, in turn, affect expansion [33]. Interaction between WCF, MPF and MKF had a significant positive effect. EI had values ranging from 1.03 ± 0.05 to 1.19 ± 0.01. EI increased in the vertex of 75% WCF. The design points that had the highest values were mixtures 1, 3, 6, 10 and 12. Among the design points, the maximum desirability (0.91) was reached in mixture 1 (75%WCF/25%MPF).

The most common way to express expansion is the expansion index, which is the ratio of the diameter of an extrudate and the diameter of the die. Studies on by-products in extrusion processing have shown that as the by-product content increases, the expansion ratio decreases, and the density of the extrudates increases. Lower EI values can be attributed to starch dextrinization due to shear and temperature during extrusion. The EI is reported to increase under conditions of high temperature and low moisture, as lower moisture imparts higher shear rates and improves the viscoelastic properties of the melt by the degradation of starch [7]. However, the usage of raw materials with a higher content of protein and dietary fibers is known to cause lower expansion during the extrusion process, which results in unacceptable products [34].

This trend is visible in Figure 2, where the lowest value of EI was identified in mixture 8 (25% WCF/58.33% MPF/16.67 MKF%), and the highest value was found in mixture 3 (58.33% WCF/25% MPF/16.67 MKF%) (Table 3). This means that EI increases as the percentage of WCF increases and MPF decreases, as a result of the increased amounts of starch in white corn compared to mango peel and kernel flours. The reason for this could be that the lower limit of starch content to obtain a good expansion is between 60–70%. Corn contains from 62–75% of the grain [35].

In general, the starch content of extruded non-expanded products is 60% or less; in contrast to direct-expanded products that utilize starch above 80% [7]. Reports indicate that mango kernel is comparable to most cereals in respect to carbohydrates, protein, fat, and minerals. Mango kernel flour had 63.55–70.68% starch [36,37] and mango peel flour had 16.8% of starch [38], depending on the variety of mango. The EI is sought to be maximized in extruded foods, because expansion is an important quality in extruded cereal snacks in terms of functional properties and acceptability of the final product [37,38].

3.2.2. Hardness

Texture plays an important role in the acceptability of products among consumers. Defined as the sensory manifestation of food structure and the way in which this structure changes due to applied forces, it represents the combination of mechanical, geometrical, and surface characteristics of the products [39].

Hardness had a simple and two component interactions with significant effects. Table 4 shows that, WCF, MPF, MKF, WCF/MPF and WCF/MKF had significant positive effects while MPF/MKF had significant negative effect. Hardness values ranged from 63.45 ± 6.67 to 115.62 ± 15.40 N. Hardness decreased in the vertex of 75% WCF. The design points that had the lowest values were mixtures 1, 3, 6 and 10. Among the design points, the maximum desirability (1.0) was reached in mixture 1 (75% WCF/25% MPF). Expansion index and hardness are similarly affected. The increase in mango by-products generally increased the hardness of the extrudates because their expansion decreases. For example, the hardness of corn-mango peel extrudates increased as the mango peel content exceeded 8% [7].

This trend is shown in Figure 2b, where the lowest hardness value was in mixture 10 (25% WCF/25% MPF/50% MKF) and the highest value was in mixture 7 (25% WCF/75% MPF) (Table 3). This means that hardness decreases as the percentage of MPF decreases as a result of the higher amount of fiber in mango, and the kernel flour has similar values of starch as the cereals. The soluble and insoluble fiber content in mango peel powders from the Tommy Atkins mango variety was more than 23% and 16%, which correspond to 20 g and 14 g of soluble and insoluble fiber, respectively, per 100 g of mango peel powder [40]. These values are similar to those reported by de Lourdes García-Magaña et al. [41] who found values of 38.7 g for total dietary fiber, which correspond to 12.1 g and 26.6 g of soluble and insoluble fiber, respectively, for every 100 g of mango peel of the Tommy Atkins variety. The values in this study differed from those in Hincapié et al. [42], who reported that differences in fiber content may be due to the water removal process, pre-harvest conditions, and the ripeness of the mango, although in all cases, the fiber content can be considered high.

Table 3. Results of the response variables of the mixture design.

Mixture	EI [1,2]	Hardness [1] (N)	WAI [1,3] (g Wet/g Sample)	WSI [1,4] (%)	Total Polyphenol [1] (mg GAE/100 g Sample)	DPPH [1] (mg Etrolox/g Sample)	ABTS [1] (mg Etrolox/g Sample)
1	1.18 ± 0.01 ^{a,b}	63.55 ± 13.34 ^{a}	4.67 ± 0.10 ^{a,b}	14.20 ± 0.49 ^{a}	4821 ± 32.87 ^{a}	101.38 ± 3.21 ^{a}	133.53 ± 8.81 ^{a}
2	1.10 ± 0.01 ^{d,e}	85.91 ± 14.81 ^{c,d}	4.41 ± 0.04 ^{a,c}	21.43 ± 0.54 ^{b,c}	6055 ± 44.26 ^{a}	123.63 ± 6.29 ^{b,c}	151.80 ± 7.50^{a,b}
3	1.19 ± 0.01 ^{b}	64.14 ± 12.55 ^{a}	4.03 ± 0.05 ^{d,e}	17.46 ± 0.11 ^{d}	5294 ± 32.54 ^{a}	158.54 ± 6.52 ^{e}	100.71 ± 2.86 ^{e}
4	1.07 ± 0.01 ^{e,f}	109.83 ± 16.67 ^{f,g}	4.46 ± 0.02 ^{a}	29.12 ± 0.44 ^{e}	6548 ± 38.91 ^{a}	104.38 ± 3.59 ^{a,b}	165.87 ± 7.46 ^{b,c,d}
5	1.09 ± 0.01 ^{d,e,f}	87.77 ± 13.14 ^{c,d,e}	4.63 ± 0.16 ^{a,b}	22.20 ± 0.16 ^{c}	7157 ± 42.23 ^{a}	173.77 ± 6.94 ^{f,g}	265.74 ± 9.32 ^{f}
6	1.17 ± 0.03 ^{a,b}	67.86 ± 10.98 ^{a,b}	4.42 ± 0.10 ^{a}	17.02 ± 0.29 ^{d}	6997 ± 48.82 ^{a}	198.93 ± 6.07 ^{h,i}	173.18 ± 6.83 ^{d}
7	1.05 ± 0.02 ^{f,g}	115.62 ± 15.40 ^{g}	5.78 ± 0.11 ^{f}	31.51 ± 0.69 ^{f}	7242 ± 46.40 ^{a}	134.71 ± 6.59 ^{c,d}	212.67 ± 9.64 ^{g}
8	1.03 ± 0.05 ^{g}	96.40 ± 12.75 ^{d,e}	4.46 ± 0.01 ^{a}	30.20 ± 0.14 ^{g}	5069 ± 16.60 ^{a}	173.26 ± 6.53 ^{e,f}	128.05 ± 5.16 ^{a}
9	1.12 ± 0.02 ^{c,d}	74.73 ± 11.47 ^{a,b,c}	4.85 ± 0.08 ^{b}	21.94 ± 0.14 ^{c}	7455 ± 52.26 ^{a}	192.60 ± 6.32 ^{g,h}	284.77 ± 12.0 ^{f}
10	1.15 ± 0.01 ^{a,c}	63.45 ± 6.67 ^{a}	3.37 ± 0.03 ^{g}	20.66 ± 0.25 ^{b}	7365 ± 42.22 ^{a}	209.24 ± 7.55 ^{i}	380.00 ± 10.4 ^{h}
11	1.09 ± 0.01 ^{d,e,f}	85.42 ± 11.67 ^{c,d}	3.82 ± 0.04 ^{e}	24.04 ± 0.23 ^{h}	6942 ± 46.16 ^{a}	157.56 ± 7.59 ^{d,e}	170.08 ± 3.58 ^{c,d}
12	1.15 ± 0.04 ^{a,c}	83.45 ± 8.53 ^{c,d}	4.14 ± 0.01 ^{c,d}	19.41 ± 0.16 ^{i}	6530 ± 42.02 ^{a}	128.12 ± 4.29 ^{c,d}	153.87 ± 6.95 ^{a,b,c}
13	1.06 ± 0.02 ^{e,f,g}	101.11 ± 13.24 ^{e,f}	4.42 ± 0.18 ^{a}	28.52 ± 0.05 ^{e}	7028 ± 44.89 ^{a}	150.03 ± 6.81 ^{e}	175.56 ± 5.55 ^{d}
14	1.12 ± 0.03 ^{c,d}	79.73 ± 9.12 ^{b,c}	3.86 ± 0.05 ^{e}	24.47 ± 0.16 ^{h}	7493 ± 50.15 ^{a}	189.82 ± 7.34 ^{g,h}	243.66 ± 3.09 ^{i}

Identical letters on the same columns are statistically equal (HSD Tukey, $p < 0.05$). [1] Mean ± SD. [2] EI: Expansion Index, [3] WAI: Water absorption Index, [4] WSI: Water Solubility Index.

Table 4. Regression coefficients and correlation for the adjusted model to experimental data in D-optimal mixtures design for physical and chemical properties.

Variable	λ_1 (WCF) [1]	λ_2 (MPF) [2]	λ_3 (MKF) [3]	$\lambda_1 \lambda_2$	$\lambda_1 \lambda_3$	$\lambda_2 \lambda_3$	$\lambda_1 \lambda_2 \lambda_3$	Pred-R^2
Physical properties								
EI [4]	1.175	1.014	1.15	N.S. [7]	N.S. [7]	N.S. [7]	N.S. [7]	85.62
Hardness	62.26	115.76	63.68	44.91	24.07	−13.28	N.S. [7]	97.20
WAI [5]	4.26	5.15	3.73	N.S. [7]	N.S. [7]	N.S. [7]	N.S. [7]	47.49
WSI [6]	15.34	33.37	20.32	N.S. [7]	N.S. [7]	N.S. [7]	N.S. [7]	91.86
Chemical properties								
Total Polyphenol				No model				
DPPH	110.48	134.25	225.84	N.A.	N.A.	N.A.	N.A.	90.39
ABTS	138.15	192.62	392.62	−37.44	−575.06	−401.87	2264.32	86.63

[1] White corn flour, [2] mango peel flour, [3] mango kernel flour, [4] Expansion Index, [5] Water Absorption Index and [6] Water Solubility Index, [7] N.S.: Not Significant.

The incorporation of fiber can cause texture problems, thus decreasing consumer acceptance. The hardness of extrudates generally increases with decreasing expansion index, increasing by-product contents of extrudates especially when by-products have a high insoluble fiber content. The extrudate hardness has been observed to increase with the decrease of the expansion ratio [7].

3.2.3. The Water Absorption Index (WAI)

WAI is considered an indicator of structural changes in food materials. Interaction between WCF, MPF and MKF had a significant positive effect. WAI had values ranging from 3.37 ± 0.03 to 5.78 ± 0.11. WAI increased in the vertex of 75% WPF.

The design points that had the highest values were mixtures 4 and 7. Among the design points, the maximum desirability (0.74) was reached in mixture 7 (25% WCF/75% MPF) (Figure 2c). Contreras-Jiménez et al. [43] concluded that the average WAI value for commercial flours is between 2.36–2.95, while Flores-Farías et al. [44] established that the average WAI of commercial flours is between 2.7–3.7. When comparing these values with those obtained, we can see that the values for the points of the mixture design are above those reported, only mixture 10 has this average; this is possibly because the starch underwent a high degree of dextrinization during extrusion, which caused an increase in the WAI.

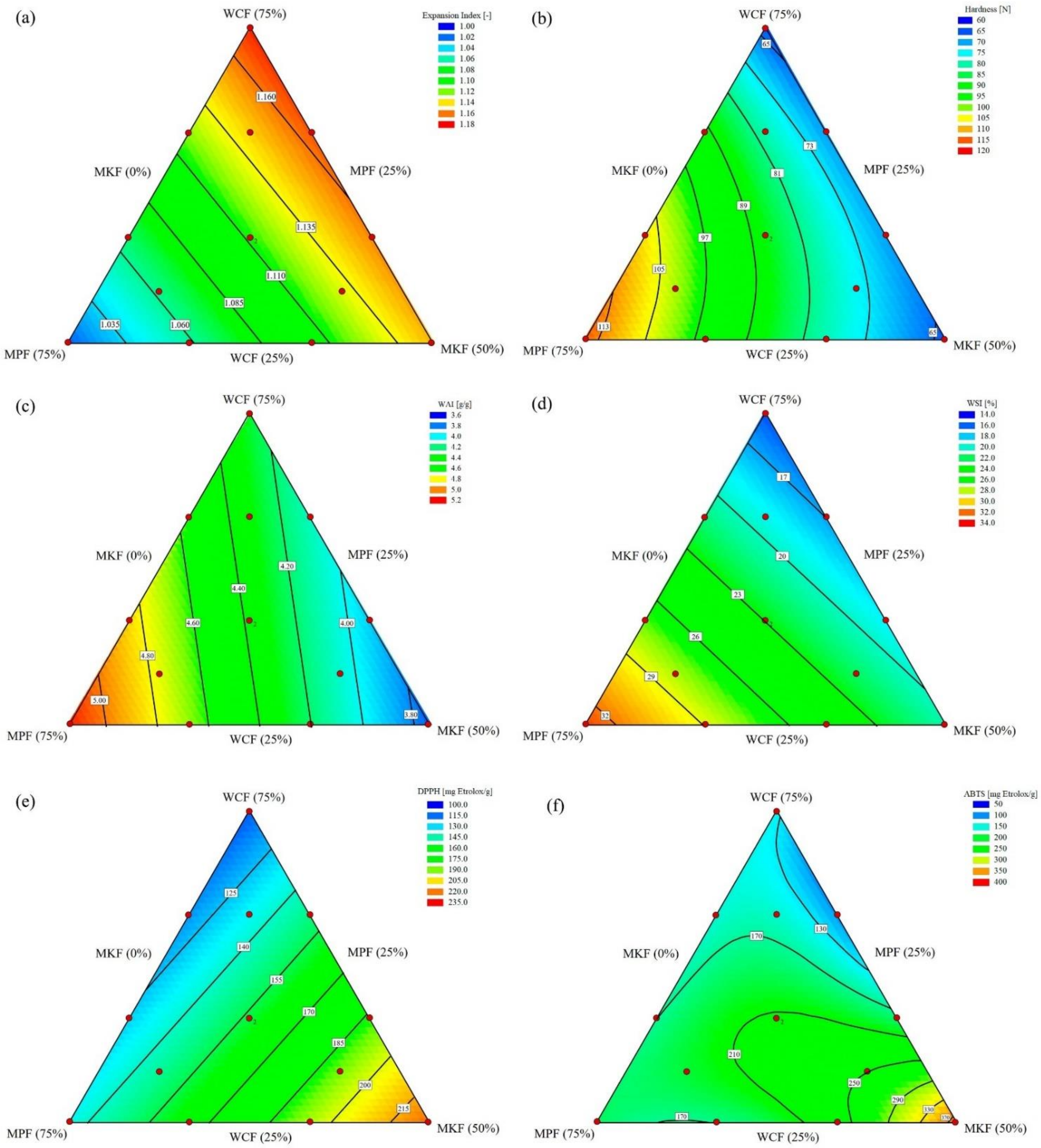

Figure 2. Estimated response of surface plots indicating effects of mixture design of white corn flour (WCF), mango peel flour (MPF) and mango kernel flour (MKF) on the physical and chemical properties of extrudate: (**a**) Expansion Index, (**b**) Hardness, (**c**) Water Absorption Index (WAI), (**d**) Water Solubility Index (WSI), (**e**) DPPH, (**f**) ABTS.

In most cases, WAI increased with increased by-product contents. The initial water absorption characteristics of by-products with high fiber contents and expansion ratios affects WAI [7]. This trend is shown in Figure 2c, with the lowest value of WAI found in mixture 10

(25% WCF/25% MPF/50% MKF) and the highest value in mixture 7 (25%WCF/75%MPF) (Table 3). This means that WAI increases as the percentage of MPF increases, due to the addition of by-products usually reducing the WAI of extrudates, which has been attributed to the relative decrease in starch content and competition of absorption of water between by-products and available starch [45].

The Water Absorption Index (WAI) and Water Solubility Index (WSI) are important qualities related to the bowl-life of breakfast cereals and the mouthfeel of direct-expanded snacks. WAI and WSI values may depend on the expansion ratio and the initial water absorption characteristics of raw materials, especially when by-products with high fiber contents are added. However, these two properties are significantly influenced by the combined effects of raw materials, the expansion of the extrudates, and the processing conditions [7].

According to Altan et al. [45], protein denaturation, starch gelatinization, and swelling of fiber can be responsible for the increased WAI of extruded products, and a moderate extrusion condition disrupts structures, which create pores that water can penetrate.

3.2.4. The Water Solubility Index (WSI)

The WSI is related to the quantity of soluble molecules, which is related to dextrinization. Interactions between WCF, MPF and MKF had significant positive effects. WSI had values ranging from 14.2 ± 0.49 to 31.51 ± 0.69. WSI decreased in the vertex of 75% WCF.

The design points with the lowest values were mixture 1 and 3. Among the design points, the maximum desirability (0.93) was reached in mixture 1 (75% WCF/25% MPF). The WSI reflects the degree of starch degradation. Contreras-Jiménez et al. [43] concluded that the average WSI value for commercial flours is between 7.19–13.31%, while Flores-Farías et al. [44] established that the average WSI of commercial flours is between 4–12%. When comparing these values with those obtained, we can see that the values for the points of the mixture design are above those reported. The WSI is often used as an indicator of degradation of molecular components.

The overall WSI values of extrudates decreased with increasing by-product inclusion. This could be attributed to the degradation of starch and the breakdown of soluble fiber at a high energy input of extrusion due to the low moisture content. In most cases, WSI decreased with increased by-product contents. WSI is proportional to the expansion ratio [7].

The WSI is raised due to the disintegration of starch granules and low molecular compounds from extrudate melt during the extrusion process, this may cause an increase in soluble material. This trend is shown in Figure 2d, where the lowest value of WSI was found in mixture 1 (75% WCF/25% MPF) and the highest value was in mixture 7 (25% WCF/75% MPF) (Table 3). This means that WSI decreases as the percentage of MCF increases and the decreases in MPF are similar to those reported to Jin et al. [46], who observed an increase in the WSI of corn meal extrudates as the fiber content increased from 0 to 20%. The reason for this is that water solubility gives information about degradation, and different results have been observed for the effect of the incorporation of food by-products on the functionality of extrudates [47].

3.3. Chemical Properties of Extrudates

3.3.1. Total Polyphenol

Phenolic compounds are useful in the formulation of increasingly healthy and safe nutritional products, which are in growing demand from consumers concerned about their health [48]. Interactions between WCF, MPF and MKF did not significantly affect total polyphenol. No model was found to fit for total polyphenol (p = 0.0526).

The number of total phenols of extrudates in the mixture design ranged from 4821 ± 32.87 to 7493 ± 50.15 mg GAE/100 g sample (Table 3). The lowest value of total phenols was in mixture 1 (75% WCF/25% MPF) and the highest value was in mixture 14 (33.33% WCF/33.33% MPF/33.33 MKF). This means that total phenols increase as the percentage of MKF and MPF increases and WCF decreases. One explanation could be that the concentration of phenolic compounds in the mango kernel was 4.6 times higher than those in the pulp, making these promising residues a good polyphenolic source. According to Masud et al. [11] mango kernel flour can be used in the manufacturing of cakes, cookies and breads for adults and children.

Antioxidants are substances that prevent the oxidation of molecules, particularly fat and fat containing foods. The antioxidant activity of most foods is mainly driven by phenolic compounds. The extrusion process caused a significant increase in total phenolic content and antioxidant of the extrudates by 1.92–7.94% and 1.07–5.55%, respectively. This may be attributed to the increased release of bioactive compounds from the cell wall matrix due to the extrusion process, that were thus accessible in the extraction [6].

3.3.2. Antioxidant Activity

DPPH

Antioxidants are chemical compounds that the body uses to eliminate free radicals, which are very reactive chemical substances (due to their instability) that are responsible for introducing oxygen into cells and oxidizing the different cell components [49].

Interaction between WCF, MPF and MKF had significant positive effects. DPPH had values ranging from 101.38 $\pm$ 3.21 to 209.24 $\pm$ 7.55 mg E Trolox/g sample. DPPH increased in the vertex of 50% MKF. The design points that had the highest values were mixtures 9 and 10. Among the design points, the maximum desirability (1.0) was reached in mixture 10 (25% WCF/25% MPF/50% MKF), shown in Figure 2e. The lowest value of DPPH was found in mixture 1 (75% WCF/25% MPF) and the highest value was in mixture 10 (25% WCF/25% MPF/50% MKF) (Table 3). This means that DPPH increases as the percentage of MKF increases, because of the higher antioxidant capacity in mango kernel flours as measured by DPPH.

Abdul Aziz et al. [38] obtained values of DPPH in the green and mature peel of 217 and 173 mg E Trolox/g sample, while in the extraction of antioxidants from mango peel values of 13.30 mg Etrolox/g were obtained. Sogi et al. [50] reported that the kernel varied from 328 to 450 mg E Trolox/g sample according to the drying method. The mango peel showed a lower activity, 44 to 55 mg E Trolox/g sample. These values agree with this work, because the 50% antioxidant capacity measured by DPPH contained in the extrudate is due to the influence of the mango almond. This makes the integral exploitation of the mango a possibility. Furthermore, mango peel flour could also be developed as a functional ingredient with more effective antioxidant properties [38]. Thus, the incorporation of Mango Peel Powder into biscuits increases health benefits by increasing antioxidant properties and dietary fiber content [51].

ABTS

The physiological activities of natural antioxidants are antibacterial, antiviral, antimutagenic, antiallergic, anticarcinogenic, antiulcer, anticariogenic, antimicrobial, antifungal, and inhibit blood pressure increases [52].

ABTS had a simple and two component interactions with significant effects. Table 4, WCF, MPF, MKF and WCF/MPF/MKF had positive effects on ABTS while WCF/MPF, WCF/MKF and MPF/MKF showed negative effects. ABTS had values ranging from 100.71 $\pm$ 2.86 to 380.0 $\pm$ 10.4 mg E Trolox/g sample. ABTS increases the vertex of 50% MKF. The design points that had the highest values were mixtures 10 and 14. Among the design points, the maximum desirability (1.0) was reached in mixture 10 (25% WCF/25% MPF/50% MKF), shown in Figure 2f. The lowest value of DPPH was found in mixture 3 (58.33% WCF/25% MPF/16.67% MKF) and the highest value was in mixture 10 (25% WCF/25% MPF/50% MKF) (Table 3). This means that ABTS increases as the percentage of MKF increases, as a result of its high antioxidant capacity.

Sogi et al. [50] found that mango kernel had an antioxidant capacity in the range of 277.86 to 431.50 mg E Trolox/g sample, while the peel had smaller values of 42.05 to

49.31 mg E Trolox/g sample. The antioxidant activity of 170 and 288 mg E Trolox/g sample has been reported in the metabolic extract of peel and kernel, respectively [53]. These values agree with this work in most mixtures, and we only found a few outliers in mixture 10 that had a higher ABTS than expected.

3.4. Mixture Design

The best models to be fitted for the data were chosen on the basis of the highest R^2 and p-values less than 0.05. Following these guidelines for physical and chemical parameters, a linear model was found to be the best for EI (p = 0.0000), WAI (p = 0.0289), WSI (p = 0.0000) and DPPH (p = 0.0000).

For the hardness parameter (p = 0.0388), a quadratic model was fitted. A special cubic model was found to be the most accurate for the ABTS (p = 0.0492) parameter. The models were developed as shown in Table 4. No model was found to fit for total polyphenol (p = 0.0526). The results of R^2 are in Table 4. The values in the predictive equation for various parameters indicated the goodness of fit, while coefficients of determination higher than 0.75 identified models that were adequate for parameter prediction [54].

3.5. Optimization Mixture Design

Numerical optimization was carried out through the superposition of the different response surfaces based on the variables that were significant ($p < 0.05$). Optimum formulation was obtained based on maximum EI, WAI, DPPH, ABTS and minimum Hardness and WSI of the extrudate. The impact factor of the variables was 5 for the physical properties (EI, Hardness, WAI, WSI) and 1 for the chemical properties (ABTS, DPPH) [29].

Physical properties have a greater impact than chemical properties because we want to obtain a product that is accepted by the consumer and has the best characteristics. The desirability function approach converts an estimated response to a scale-free value. When the desirability value was higher than 0.63, the product quality was regarded as acceptable. The product was considered unacceptable when the desirability value was lower than 0.37 [55]. The highest desirability corresponds with values of 0.56 to 0.64, and this region includes mixtures A, C and G. Figure 3. With these points a hedonic test of consumers of nine points was carried out [28].

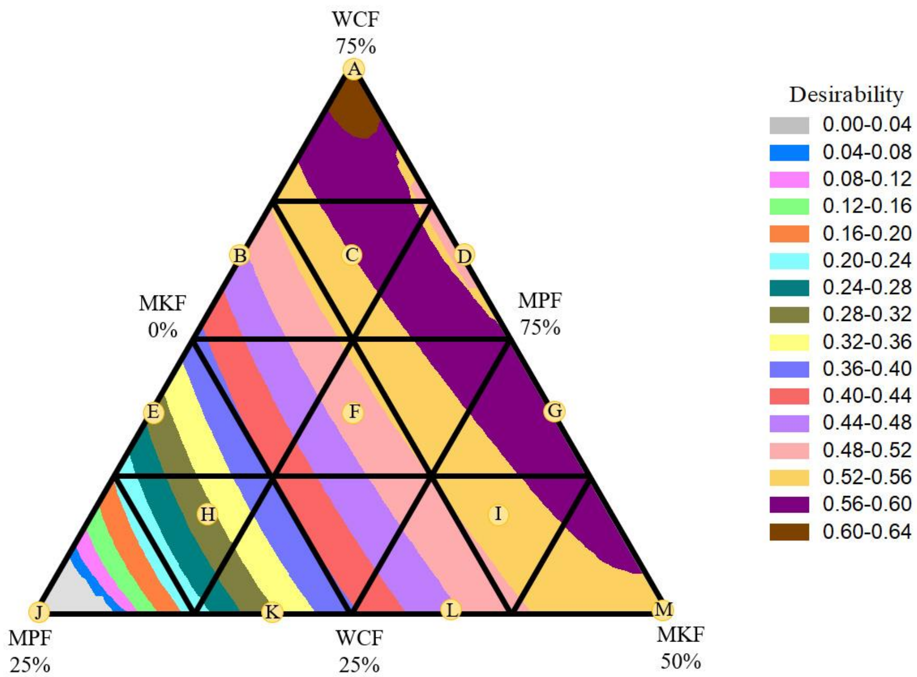

Figure 3. Simultaneous optimization of response variables for mixture design.

3.6. Sensory Evaluation of Extrudates

Sensory evaluation is the science that is responsible for perceiving the organoleptic characteristics of food (color, smell, taste, and texture) through the body's senses. It is a useful tool to gauge the acceptance of a product, or to create new ones from a formulation. Sensory evaluation in the food industry is a key activity in the development of products that allows us to understand the expectations and needs of consumers; therefore, applying sensory tests allows us to build a profile of products in the market [56].

The production of nutritionally fortified snack products with the acceptable physical and sensory properties is challenging. The addition of high-fiber and high-protein ingredients to starch-based raw materials significantly affects the texture, expansion, and overall acceptability of extruded snacks [57].

One hundred untrained consumer panelists were interviewed; 58% were female and 42% male. p-values were less than 0.05 for taste (p = 0.0000) and texture (p = 0.0126), meaning that they were statistically significant. However, the appearance attribute was not statistically significant (p = 0.0663) (Table 5). This behavior could be attributed to the introduction of a new product. Van Trijp and Van Kleef, [58] affirm that human beings, particularly in the food field, tend to show a contradictory attitude towards the new. On the one hand, there is a taste for the new, but on the other there is an avoidance of everything that is not known. It has even been proposed that the creation of new products should rarely be radically innovative, otherwise they would face a high degree of resistance from consumers [59]. That is why maintaining the base of the extrudate in white corn flour is vital since it would give us a greater acceptance value of the product.

With the analysis of HSD Tukey means we can differentiate the homogeneous groups between appearance, taste, and texture. Appearance was not statistically significant, however, taste and texture had statistically significant differences between the mixtures with a 95.0% confidence level. Taste and texture both had two groups (Table 5).

Table 5. HSD Tukey means tests.

	Appearance	
Mixture 1 *	Mixture 6 *	Mixture 12 *
6.63 ± 1.45^{a}	6.12 ± 1.55^{a}	6.37 ± 1.61^{a}
	Taste	
Mixture 1 *	Mixture 6 *	Mixture 12 *
6.80 ± 1.47^{a}	5.50 ± 1.85^{b}	6.49 ± 1.55^{a}
	Texture	
Mixture 1 *	Mixture 6 *	Mixture 12 *
6.42 ± 1.77^{a}	5.68 ± 1.84^{b}	$6.19 \pm 1.77^{a,b}$

Identical letters on the same line are statistically equal (HSD Tukey, $p \leq 0.05$). * Mean ± SD, n = 100.

Groups with the highest score were mixtures 1 and 12, so either of the two formulations could be used. Since the desire is to use mango by-products in an extruded food, mixture 12 was selected as the best extruded mixture (Figure 4). Consumers emphasized the bitter taste of the extrudate and how this characteristic influenced its result. This agrees with that reported by Basu and Shivhare, [60] who noted that overall acceptability scores improved with increasing sugar concentration in mango.

Legesse and Emire, [61] expressed that in traditional food items, 20–30% of mango kernel flour without tannis can be used without adversely affecting their acceptability. Attempts have been made to partially substitute kernel flour in bakery products. Mango by-products has been incorporated in different proportions, 3% of mango peel in bread [62], 10% of mango peel in cakes [38], 10% of mango peel powder in biscuits [51], 15–25% of mango kernel in cookies [63], and a substitution of 5% of wheat flour in cupcakes [64], all of which had positive acceptability results.

Figure 4. Best extruded product in this work.

The acceptance of a product by the customer is related to their sensory perception, and it is common for highly nutritious foods to exist, but they are not accepted by consumers. That is why the sensory evaluation of food today constitutes a fundamental pillar of the design and development of new food products [56].

Table 6 shows a comparison of the use of mango by-products and others incorporated into extruded foods, as well as the effect that these have on their physical and chemical characteristics.

Table 6. Comparison of the physical and chemical characteristics of different extrudates developed with by-products.

Authors	Conditions of Extrusion	Formulation	EI [1]	H [2]	WAI [3]	WSI [4]	TP [5]	DPPH [6]	ABTS [7]
This work	Single-Screw 3:1 compression ratio 19.05 mm screw diameter Die 3 mm 17% FM [8], 120 °C, 100 rpm	58.33% White Corn Flour 33.33% Mango Peel Flour 8.33% Mango Kernel Flour	1.15 ± 0.04	83.45 ± 8.53	4.14 ± 0.01	19.41 ± 0.16	6530 ± 42.02	128.12 ± 4.29	153.87 ± 6.95
Mazlan et al. [8]	Single-screw extruder 4:1 compression ratio Die 4 mm 17% FM [8], 100 rpm, 144 °C	17.09% Mango Peel Flour 82.91% Corn Grits	2.06 ± 0.02	64.88 ± 3.16	N.E. [9]	N.E. [9]	N.E. [9]	N.E. [9]	N.E. [9]
Korked et al. [20]	Single-Screw extruder 4:1 compression ratio 14% FM [8], 180 rpm, 180 °C	72.6% Corn Grits 8% Wheat Flour 8%Rice Flour 0.5% Margarine 5.45% Defatted soybean melt 5.45% Mango peel fiber	3.18 ± 0.11	297 ± 11.51	N.E. [9]	N.E. [9]	929 ± 0.70	N.E. [9]	N.E. [9]
Alam et al. [65]	Co-rotating Twin-screw 85% FM [8], 313 rpm, 164 °C	85% Rice flour 7.5% Defatted soy flour 3.75% Carrot pomace powder 3.75% cauliflower trimmings powder	1.06	55.2	5.8	20.1	N.E. [9]	N.E. [9]	N.E. [9]
Gumul et al. [66]	Single-Screw Die 3 mm 1:2 compression ratio 14% FM [8], 190 rpm, 180 °C	10% Defatted Blackcurrant seed 90% Cornmeal	2.80 ± 0.01	26.4 ± 3.58	9.92 ± 0.57	14.94 ± 0.72	N.E. [9]	N.E. [9]	N.E. [9]

[1] EI: Expansion Index (-), [2] H: Hardness (N), [3] WAI: Water Absorption Index (g wet/g sample), [4] WSI: Water Solubility Index (%), [5] TP: Total Polyphenol (mg EAG/100 g sample), [6] DPPH (mg Etrolox/g sample), [7] ABTS (mg Etrolox/g sample), [8] FM: Feed Moisture, [9] N.E.: Not Evaluated.

The advantages of the developed method is that a greater quantity of peel is used, obtaining a hardness 3.5 times less than the extrudate that contained 5.45% of mango peel fiber; it has a higher amount of antioxidant compounds than the study by Korked et al., who used 5.45% mango peel fiber; WAI and WSI values are within what is reported in the literature; this work has a sensory evaluation study lacking in other studies; most other studies have focused on other properties. Likewise, the disadvantages were that it worked with extrusion conditions based on references; no information was reported as to the control extrusion conditions; it used non-defatted almond, which limited the addition of this by-product due to astringency.

4. Conclusions

In this study, we found that a total of 41.67% of mango by-products can be incorporated: 33.33% mango peel and 8.34% mango kernel. These amounts are higher than those used in previous works. It is important to note that previous research focused on single by-products, and this study marks the first use of a blend of mango peel and kernel. This research is a step toward reducing the large amounts of mango by-products that are not used today. The product we developed was accepted by the consumer. Therefore, it is not only possible to obtain an extruded product with mango by-products, but also to obtain a product that is accepted for human consumption, with the physical and chemical properties of the extrudate able to be used to prepare a breakfast cereal. Finally, future research could focus on optimization processes in more sophisticated equipment with industrial capacity, as well as on the nutritional profile that mango by-products can contribute. The analysis of all these characteristics indicates that the extrudate with mango peel and almond had outcomes similar to those expected from the literature, although it had a greater impact in that a high percentage of mango by-products were accepted by potential consumers.

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