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Physicochemical and Techno-Functional Properties of Extruded Corn Starch Snacks Enriched with Huitlacoche (*Ustilago maydis*): Effects of Extrusion Parameters and Process Optimization

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Abstract

The main objective of this research was to evaluate the effect of extrusion temperature (ET), feed moisture content (FMC), and the proportion of huitlacoche relative to corn starch (HCP/Starch) on the physicochemical, techno-functional, and color properties of an extruded snack, using response surface methodology to optimize processing conditions and product quality. A Box–Behnken design and response surface methodology were used to model and optimize the process. The responses analyzed included residence time (RT), specific mechanical energy (SME), expansion index (EI), bulk density (BD), texture (Tex), water absorption index (WAI), water solubility index (WSI), pH, and color parameters (L^*, a^*, b^*, C*, h°, and ΔE). Results showed that the huitlacoche proportion significantly affected BD, Tex, WSI, and color, while ET and FMC mainly influenced EI, SME, and other techno-functional traits. Multi-response optimization indicated that 150.4 °C, 15.8 g/100 g FMC, and 10–20 g/100 g HCP/Starch maximized EI (2.27) and minimized BD (0.40 g/cm^3), Tex (17.5 N), and SME (347.6 J/g). The overall performance was summarized by global desirability (0.83–0.88), a metric that combines all responses into a single scale (0 = poor; 1 = is the most desired goal). The optimized conditions produced snacks with acceptable hydration capacity, pH, and color, supporting huitlacoche as a viable functional ingredient. These findings demonstrate the potential of this traditional resource for developing sustainable, value-added, and health-oriented extruded foods.

Keywords: huitlacoche; extrusion; response surface methodology; functional snack; multivariate optimization

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1. Introduction

Extrusion is a widely used technology in the food industry for the production of ready-to-eat products such as breakfast cereals, meat analogs, and expanded snacks. This process

combines high temperature, pressure, and shear forces over short residence times, enabling the modification of ingredient structure and functionality, improving digestibility, and extending product shelf life [1–3]. Additionally, extrusion offers a versatile platform for the incorporation of functional ingredients and agro-industrial by-products in the development of healthier and more sustainable foods [3–6].

Corn starch-based extruded snacks dominate the ready-to-eat market due to their expansion capacity, crunchy texture, and consumer acceptance [7–9]. These products also serve as an effective vehicle to incorporate functional ingredients such as mushrooms and agro-industrial by-products to enhance nutritional value [3,10,11].

In recent years, there has been growing interest in incorporating edible mushrooms [12,13] as functional ingredients in extruded snacks due to their high nutritional value, quality protein profile, dietary fiber content, and bioactive compounds with antioxidant, hypocholesterolemic, and antitumor properties [11,14,15]. According to the global mushroom market report, the global market for mushrooms is estimated to grow from US$48.8 to 83.5 billion over the period from 2022 to 2030 at a compound annual growth rate of 7% [16]. Species such as *Pleurotus ostreatus* (oyster mushroom), *Lentinula edodes* (shiitake), and *Volvariella volvacea* (straw mushroom) being the most used, as their powders have been successfully integrated into various formulations to enhance the nutritional profile of extruded products.

For instance, Sudhakar et al. [17] developed extruded snacks from rice flour and oyster mushroom powder blends, reporting that the inclusion of up to 6.6% mushroom significantly improved fiber and protein content without negatively affecting the physical properties of the extrudates. Tepsongkroh et al. [10] evaluated the sensory acceptance of snacks formulated with brown rice and different mushroom types, showing that the incorporation of *Pleurotus pulmonarius* and *Volvariella volvacea* powder, in combination with seasonings, significantly increased consumer acceptance and evoked positive emotions such as interest and satisfaction. Moreover, the inclusion of oyster mushroom has been reported to enhance product stability during storage, particularly when high-barrier packaging materials such as metallized polypropylene are used [14]. These findings support the use of edible mushrooms as an effective strategy to improve the nutritional and functional profile of extruded products, offering opportunities for the development of innovative, health-oriented foods. However, their inclusion also affects the flow behavior, expansion, and texture of extrudates due to their low starch content and high insoluble fiber proportion, which necessitates careful optimization of process parameters such as extrusion temperature, feed moisture content, and functional ingredient ratio [4,5].

In this regard, statistical tools such as response surface methodology (RSM) are essential for modeling the behavior of multiple extrusion variables and for determining the optimal conditions that balance product quality and functionality [17]. Within this context, huitlacoche (*Ustilago maydis*), a fungus endemic to Mexico with deep culinary tradition, represents an innovative and culturally relevant alternative for the development of functional extruded snacks. Huitlacoche is characterized by high moisture content (80–86%), protein levels of up to 12%, and dietary fiber ranging from 54 to 65%, distributed between soluble (mainly β-glucans and heteropolysaccharides) and insoluble fractions (chitin, hemicelluloses, and structural polysaccharides). It also provides essential fatty acids such as linoleic and linolenic acids, as well as bioactive compounds including phenolics, ergosterol, and polysaccharides with immunomodulatory activity [18]. These characteristics justify its classification as a functional food and support its incorporation into extruded products to improve nutritional and techno-functional quality.

Its high fiber content can restrict starch gelatinization and reduce expansion, leading to denser textures, while its phenolic compounds may interact with proteins and starch,

affecting matrix stability and crispness. These incorporation challenges highlight the importance of optimizing extrusion parameters to achieve acceptable texture and structure. Additionally, the presence of bioactive phenolics with antioxidant properties provides potential health benefits [18–20]. Therefore, the main objective of this research was to evaluate the effect of extrusion temperature (ET), feed moisture content (FMC), and the proportion of huitlacoche relative to corn starch (HCP/Starch) on the physicochemical, techno-functional, and color properties of an extruded snack, using response surface methodology to optimize processing conditions and product quality.

2. Materials and Methods

2.1. Materials

Huitlacoche galls (*U. maydis*) were purchased from the local market in San Juan Bautista Tuxtepec, Oaxaca, Mexico, with an initial moisture content of 26.81 g/100 g. The material was dried at 60 °C for 12 h, ground, and sieved to obtain a particle size of 0.25 mm. The dehydrated huitlacoche contained 5.72 ± 0.06 g/100 g of ash (dry basis, db), 9.70 ± 0.66 g/100 g (db) of protein, 4.36 ± 0.74 g/100 g (db) of lipids, and 13.56 ± 0.55 g/100 g (db) of fiber, as determined following the AOAC [21] official methods. The corn starch used was a commercial product from IMSA (Industrializadora de Maíz, S.A. de C.V., Tlalnepantla de Baz, Estado de México, México) with 98% purity and the following composition: 98 g/100 g (db) of starch, 0.62 g/100 g (db) of lipids, and 0.49 g/100 g (db) of ash. Prior to use, huitlacoche powder and corn starch were homogenized and analyzed for proximate composition, and the same batches were employed across all experimental runs to ensure reproducibility. All reagents used were of analytical grade.

2.2. Extrusion Cooking Process

Mixtures of huitlacoche powder and corn starch were prepared, adjusting the moisture content (FMC) according to the experimental design (Figure 1, Table 1). The FMC was adjusted by spraying distilled water onto the flour mixture, followed by 12 h of equilibration at 4 °C in sealed polyethylene bags. Extrusion was performed using a laboratory-scale single-screw extruder (Extruder 19/25DN, Model 832005.007, Brabender GmbH & Co. KG, Duisburg, Germany), with a barrel length of 428 mm, screw diameter of 19 mm, and a compression ratio of 3:1. A 3 mm circular die was employed. The extruder barrel was divided into four heating zones with the following temperatures: Zone 1 = 50 °C, Zone 2 = 80 °C, Zone 3 = 100 °C, and Zone 4 = 120–170 °C. The feed rate was maintained at 60 g/min and the screw speed at 200 rpm. During extrusion, the ambient temperature ranged between 23 and 25 °C and the relative humidity was 60–65%.

The ranges of extrusion temperature (120–170 °C) and feed moisture content (14–22 g/100 g) were selected based on preliminary trials and literature precedents for maize-based snacks. The proportion of huitlacoche (10–60 g/100 g) was chosen to represent typical enrichment levels used in functional extrudates while ensuring process feasibility.

Table 1. Box–Behnken experimental design used in the development of the snacks.

Independent Variables	Code	Levels		
Extrusion temperature (°C)	ET = A	120	145	170
Feed moisture content (g/100 g)	FMC = B	14	17	20
Huitlacoche/Starch proportion (g/100 g)	HCP/Starch = C	10	35	60

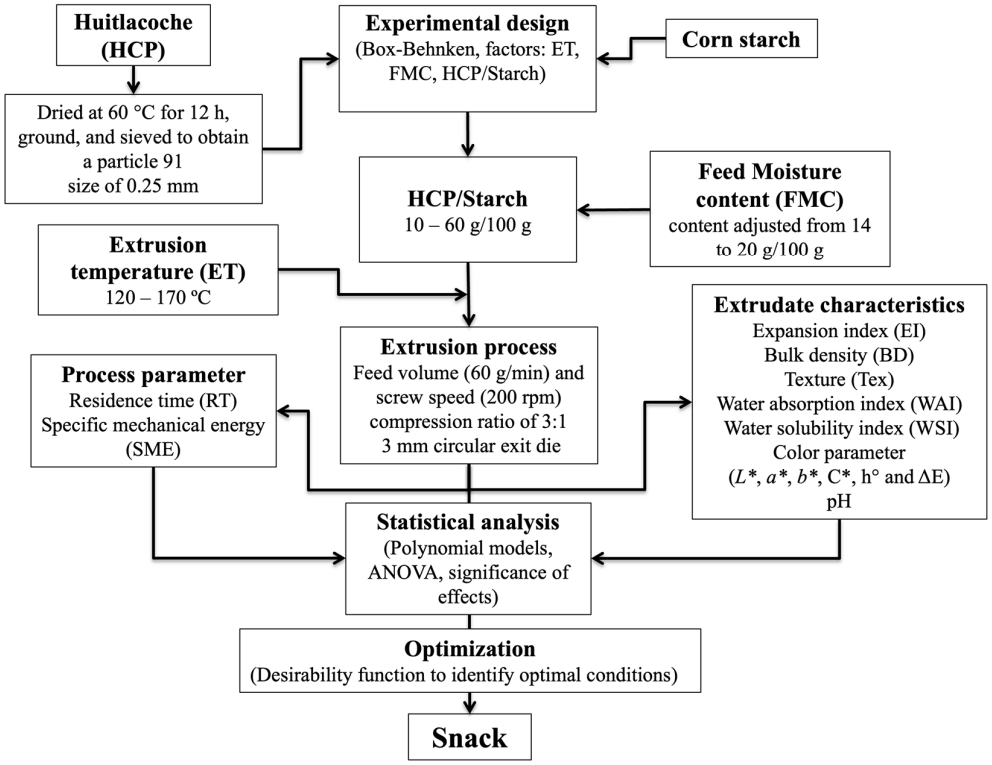


Figure 1. Response general diagram of the production and evaluation of extruded snacks based on corn starch enriched with huitlacoche.

2.3. Variables of the Extrusion Process

Residence Time (RT) and Specific Mechanical Energy (SME)

The RT was determined according to the procedure described by Rivera-Mirón et al. [4]. SME (J/g), defined as the total mechanical energy required to produce 1 g of extruded product, was calculated using the equation proposed by Rivera-Mirón et al. [4]. (Equation (1)). For each treatment, four independent measurements were recorded during the extrusion process to ensure reproducibility.

$$SME = \frac{\Omega \times \omega \times 60}{M_{feed}} \quad (1)$$

where Ω is the net torque exerted on the extruder (N m), ω is the angular speed of the screw (radians/s), and M_{feed} is the total flow (g/min).

2.4. Characterization of Extruded Products

2.4.1. Expansion Index (EI) and Bulk Density (BD)

The EI of the extruded material was determined as the average of 15 random measurements taken using a Vernier caliper (Truper S.A. de C.V. Model: IP54, Jilotepec, Mexico). EI was calculated according to Equation (2), as described by Ramírez-Rivera et al. [1]:

$$EI = \frac{Extrudate\ diameter}{Die\ diameter} \quad (2)$$

Bulk density (BD) was determined following the methodology described by Ramírez-Rivera et al. [1]. The volume of the expanded sample was measured using the seed displacement method in a 100 mL graduated cylinder. For each trial, the volume displaced by 20 g of randomly selected samples was recorded, and all measurements were performed

in triplicate. BD was calculated as the ratio of sample weight to the volume displaced in the cylinder, as shown in Equation (3).

$$BD = \frac{4\,m}{\pi d^2 L} \tag{3}$$

where m is mass, g of a length L, cm of extrudates with diameter d, cm.

2.4.2. Texture (Tex)

Tex was measured using a TA-XT2 Plus texture analyzer (Texture Technologies Corp., Scarsdale, NY, USA/Stable Micro Systems, Haslemere, Surrey, UK) equipped with a 50 kg load cell. The equipment was calibrated for force and height prior to analysis. A Warner-Bratzler cutting blade (HDP/BS, Stable Micro Systems, Haslemere, Surrey, UK) was employed with the following settings: pre-test speed of 1.0 mm/s, test speed of 5.0 mm/s, post-test speed of 10.0 mm/s, distance of 30 mm, and a trigger force of 5 g. Texture force was expressed in Newtons (N), following the methodology described by Rivera-Mirón et al. [4]. Fifteen determinations were conducted per sample. Prior to testing, samples were conditioned at 25 °C for 24 h.

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

WAI and WSI were determined in triplicate following to the methodology described by Rodríguez-Miranda et al. [22], using Equations (4) and (5), respectively.

$$\text{WAI} = \frac{\text{Weight of wet sediment (g)}}{\text{Weight of dried sediment (g)}} \tag{4}$$

$$\text{WSI}(\%) = \frac{\text{Solids solubles weight(g)}}{\text{Weight of dried sediment(g)}} \times 100 \tag{5}$$

2.4.4. Color Parameters and pH

The color of the extruded samples was measured in triplicate using an UltraScan VIS tristimulus colorimeter (MiniScan Hunter Lab, model 45/0L, Hunter Associates Lab., Inc. Reston, Virginia, USA). The L^*, a^*, and b^* values were recorded and used to calculate chroma (C*), hue angle (h°), and total color difference (ΔE), according to the following equations:

$$C^* = \sqrt{(a^2 + b^2)} \tag{6}$$

$$h^o = Tan^{-1}\left(\frac{b^*}{a^*}\right) \tag{7}$$

$$\Delta E = \sqrt{\left[\left(L^* - L_0^*\right)^2 + \left(a^* - a_0^*\right)^2 + \left(b^* - b_0^*\right)^2\right]} \tag{8}$$

where $L_0^* = 97.63$, $a_0^* = 0.78$, y $b_0^* = 0.25$, correspond to the respective readings of the standard white reference.

The pH was measured using a potentiometer (Thermo Scientific Inc., Model Orion Star A211 pH/mV RmV®, Waltham, MA, USA), previously calibrated with buffer solutions at pH 4, 7 and 11. The measurement were performed in triplicate by dispersing 1 g of flour in 10 mL of distilled water at 25 °C.

2.5. Experimental Design and Statistical Analysis

RSM was applied to estimate the effect of the independent variables: extrusion temperature (A), feed moisture content (B), and proportion of huitlacoche in corn starch (C, Table 1) on RT, SME, EI, BD, Tex, WAI, WSI, pH, and color parameters (L^*, a^*, b^*, C*,

h°, and ΔE). A Box–Behnken design was employed for the experimental setup (Table 1). RSM was applied to the experimental data using commercial statistical software, Design-Expert version 7.0.0 (Stat-Ease Inc., Minneapolis, MN, USA). The response functions (Y) represented the experimental responses, while A, B, and C were the independent variables modeled using a second-order polynomial equation (Equation (9)):

$$Y = b_0 + b_1A + b_2B + b_3C + b_{11}A^2 + b_{22}B^2 + b_{33}C^2 + b_{12}AB + B_{13}AC + B_{23}BC \quad (9)$$

The coefficients of the polynomial model were represented as follows: b_0 (constant), b_1, b_2, and b_3 (linear effects), b_{11}, b_{22}, and b_{33} (quadratic effects), and b_{12}, b_{13}, and b_{23} (interaction effects). Variables with a significance level of $p < 0.05$ were selected for model construction. The fitted polynomial equations were expressed as surface plots to visualize the relationship between the response and the experimental factor levels, as well as to interpret optimal conditions. Numerical optimization was performed using the Design-Expert software [5]. The goal of the optimization process was to identify processing conditions and the proportion of huitlacoche and corn starch that would maximize expansion while minimizing energy consumption, i.e., maximizing EI, minimizing BD, Tex, and SME, and maintaining RT, WAI, WSI, pH, *L**, *a**, *b**, C*, h°, and ΔE within acceptable ranges, as defined by the Design-Expert 7.0 software (Stat-Ease Inc., Minneapolis, MN, USA). The complete models were used to predict the dependent variables at the optimal point based on desirability functions.

3. Results and Discussion

3.1. Residence Time (RT)

The RT is a critical variable in extrusion since it influences starch gelatinization, protein denaturation, energy transfer and final texture of the extrudate [8,23]. The RT values ranged from 191.59 to 438.83 g/min (Table 2). The RT was significantly influenced ($p < 0.05$) by the HCP/Starch ratio (Table 4). The fitted model for this variable exhibited a determination coefficient of $R^2 = 0.76$ (Tables 4 and 5), indicating a suitable predictive capacity. Figure 2d shows that, at a constant HCP/Starch ratio, increasing ET reduces RT, with a more pronounced effect under low moisture conditions. This phenomenon is attributed to a decrease in melt viscosity at elevated temperatures due to faster gelatinization and denaturation of biopolymers, which facilitates greater material flow through the extruder [5,7].

In contrast, FMC exhibited a positive effect on RT (Table 4), indicating that higher water content increases residence time. This is related to the lubricating effect of water, which reduces internal friction and decreases the melt flow rate. This behavior is consistent with findings by Lotfi-Shirazi et al. [5], who reported decreased RT at low moisture levels due to reduced barrel fill and intensified friction between the screw and the mass.

The HCP/Starch ratio showed a significant negative effect on RT, suggesting that increasing the inclusion of huitlacoche leads to shorter residence times. This may be attributed to the high content of fiber, proteins, and lipids in huitlacoche, which increase viscosity and alter the melt matrix, limiting its displacement [4,24]. Similar behavior has been reported in blends enriched with vegetable by-products such as carrot pomace and whey flour [17]. Figure 2e shows that this effect is more pronounced at higher temperatures.

Furthermore, Figure 2f illustrates a positive interaction between FMC and HCP/Starch: RT slightly increases with FMC at low huitlacoche levels, but decreases at higher proportions, suggesting limited synergy. The quadratic effects of ET^2 and FMC^2 indicate an inflection point in RT at intermediate levels of moisture and temperature, confirming the nonlinear nature of this response.

Table 2. Experimental data of extruded snacks for response surface analysis.

Extrusion Process Variables			Response Variables						
ET (°C)	**FMC (g/100 g)**	**HCP/Starch (g/100 g)**	**RT (g/min)**	**SME (J/g)**	**EI**	**BD (g/cm^3)**	**Tex (N)**	**WAI (g/g)**	**WSI (%)**
120	14	35	267.46	525.08	2.21	0.51	27.89	5.43	10.79
170	14	35	240.17	456.06	2.02	0.57	30.90	5.50	8.34
120	20	35	323.85	506.34	1.72	0.70	48.40	4.13	22.91
170	20	35	304.84	271.20	1.32	0.89	19.15	5.77	11.26
120	17	10	438.83	460.09	2.20	0.60	16.60	6.48	16.64
170	17	10	361.01	373.72	2.22	0.31	12.76	6.85	16.00
120	17	60	199.91	338.69	1.20	1.13	53.68	4.25	15.79
170	17	60	188.76	361.95	1.17	0.68	19.05	4.89	14.24
145	14	10	251.65	393.08	2.81	0.32	22.32	7.07	14.34
145	20	10	240.00	350.00	1.81	0.54	26.33	5.91	14.29
145	14	60	191.59	389.13	1.05	0.69	21.76	4.35	14.57
145	20	60	215.23	274.23	1.69	0.65	59.19	4.15	21.73
145	17	35	257.71	322.14	1.81	0.56	21.41	5.15	8.72
145	17	35	257.79	321.74	1.83	0.50	21.77	5.71	8.70
145	17	35	257.87	322.54	1.80	0.62	21.06	5.52	8.74

ET = Extrusion temperature; FMC = Feed moisture content; HCP/Starch proportion = Huitlacoche/Starch; SME = Specific mechanical energy; RT = Residence time; EI = Expansion index; BD = Bulk density; Tex = Texture; WAI = Water absorption index; WSI = water solubility index.

Table 3. Experimental data of extruded snack for response surface analysis (continuation).

Extrusion Process Variables			Response Variables						
ET (°C)	**FMC (g/100 g)**	**HCP/Starch (g/100g)**	**pH**	***L****	***a****	***b****	**C***	**h°**	**ΔE**
120	14	35	5.29	45.03	1.12	4.36	4.5	75.92	54.59
170	14	35	5.08	44.89	1.58	5.53	5.75	74.07	54.81
120	20	35	5.34	39.94	0.73	2.72	2.82	74.97	59.52
170	20	35	5.35	43.41	1.32	4.66	4.84	74.16	56.19
120	17	10	5.49	46.14	0.86	4.03	4.12	78.13	53.41
170	17	10	5.50	51.04	1.50	5.88	6.07	75.75	48.80
120	17	60	5.30	40.57	0.52	2.79	2.84	79.43	58.89
170	17	60	5.27	41.47	1.26	4.25	4.43	73.59	58.09
145	14	10	5.27	51.98	1.90	6.71	6.97	74.21	47.92
145	20	10	5.71	48.42	1.34	5.93	6.08	77.16	51.38
145	14	60	5.31	41.09	0.91	3.56	3.68	75.83	58.42
145	20	60	5.05	41.92	1.17	3.59	3.77	72.14	57.59
145	17	35	5.30	42.78	1.13	4.17	4.32	74.07	57.14
145	17	35	5.31	42.41	1.16	4.40	4.56	74.21	56.42
145	17	35	5.32	42.91	1.19	4.39	4.32	74.14	55.18

ET = Extrusion temperature; FMC = Feed moisture content; HCP/Starch proportion = Huitlacoche/Starch; ΔE = total color difference.

Table 4. The regression coefficients for the response surface model in terms of coded units.

Term	RT	SME	EI	BD	Tex	WAI	WSI	pH	*L**	*a**	*b**	C*	h°	ΔE
Intercept	**257.790**	**322.140**	**1.813**	**0.560**	**21.413**	**5.460**	**8.720**	**5.310**	**42.700**	**1.160**	**4.320**	**4.400**	**74.140**	**56.247**
ET	−16.909	**−45.909**	−0.075	−0.061	**−8.089**	**0.340**	−2.036	−0.028	**1.141**	**0.304**	**0.803**	**0.851**	**−1.360**	**−1.065**
FMC	16.631	**−45.198**	**−0.194**	0.086	**6.275**	**−0.299**	**2.769**	**0.062**	**−1.163**	**−0.119**	−0.408	−0.424	−0.200	**1.118**
HCP/Starch	**−62.000**	−26.611	**−0.491**	**0.173**	**9.459**	**−1.084**	0.633	**−0.130**	**−4.066**	**−0.218**	**−1.045**	−1.065	−0.533	**3.935**
ET^2	49.400	**74.766**	−0.069	0.119	1.647	−0.002	2.020	0.005	−0.215	−0.134	−0.356	−0.341	1.265	0.500
FMC^2	−23.110	42.764	0.073	−0.011	**8.525**	−0.250	2.585	−0.050	0.833	0.161	0.354	0.419	−0.625	−0.470
$HCP/Starch^2$	−10.063	−13.294	−0.047	0.001	2.462	0.160	**4.928**	**0.075**	**2.320**	0.009	0.274	0.306	**1.320**	**−1.950**
ET-FMC	2.070	−41.530	−0.053	0.033	**−8.065**	**0.393**	−2.300	0.055	0.902	0.033	0.193	0.193	0.260	−0.888
ET-HCP/Starch	16.668	27.408	−0.013	−0.040	**−7.698**	0.068	−0.227	−0.010	−1.000	0.025	−0.098	−0.090	−0.865	0.952
FMC-HCP/Starch	8.822	−17.955	**0.410**	−0.065	**8.355**	0.240	1.803	−0.175	**1.098**	**0.205**	0.203	0.245	**−1.660**	−1.073
R^2	0.76	0.91	0.96	0.71	0.94	0.98	0.86	0.97	0.98	0.95	0.93	0.93	0.91	0.97
Lack of fit (*p*-value)	<0.0001	<0.0001	0.0053	0.0646	0.0023	0.7975	<0.0001	0.0255	0.0593	0.0369	0.0392	0.0425	0.0031	05472

Bold numbers indicate estimates of significant parameters ($p < 0.05$). ET = Extrusion temperature; FMC = Feed moisture content; HCP/Starch = Huitlacoche/Starch proportion; RT = Residence time; SME = Specific mechanical energy; EI = Expansion index; BD = Bulk density; Tex = Texture; WAI = Water absorption index; WSI = water solubility index; ΔE = total color difference.

Table 5. Response surface model for all responses.

Response	Quadratic Polynomial Model	*p* Value
RT	RT = 257.790 − 16.909*A +16.631*B − 62.000*C +49.400*A^2 − 23.110*B^2 − 10.063*C^2 +2.070*AB +16.668*AC +8.822*BC	0.0266
SME	SEM = 322.140 − 45.909*A − 45.198*B − 26.611*C +74.766*A^2 +42.764*B^2 − 13.294*C^2 − 41.530*AB +27.408*AC − 17.955*BC	0.0380
EI	EI = 1.813 − 0.075*A − 0.194*B − 0.491*C − 0.069*A^2 +0.073*B^2 − 0.047*C^2 − 0.053*AB − 0.013*AC +0.410*BC	0.0061
BD	BD = 0.560 − 0.061*A +0.086*B +0.173*C +0.119*A^2 − 0.011*B^2 +0.001*C^2 +0.033*AB − 0.040*AC − 0.065*BC	0.0384
Tex	Tex = 21.413 − 8.089*A +6.275*B +9.459*C +1.647*A^2 +8.525*B^2 +2.462*C^2 − 8.065*AB − 7.698*AC +8.355*BC	0.0143
WAI	WAI = 5.460 +0.340*A − 0.299*B − 1.084*C − 0.002*A^2 − 0.250*B^2 +0.160*C^2 +0.393*AB +0.068*AC +0.240*BC	0.0010
WSI	WSI = 8.720 − 2.036*A +2.769*B +0.633*C +2.020*A^2 +2.585*B^2 +4.928*C^2 − 2.300*AB − 0.227*AC +1.803*BC	0.0088
pH	pH = 5.310 − 0.028*A +0.062*B − 0.130*C +0.005*A^2 − 0.050*B^2 +0.075*C^2 +0.055*AB − 0.010*AC − 0.175*BC	0.0035
*L**	*L** = 42.700 +1.141*A − 1.163*B − 4.066*C − 0.215*A^2 +0.833*B^2 +2.320*C^2 +0.902*AB − 1.000*AC +1.098*BC	0.0007
*a**	*a** = 1.160 +0.304*A − 0.119*B − 0.218*C − 0.134*A^2 +0.161*B^2 +0.009*C^2 +0.033*AB +0.025*AC +0.205*BC	0.0068
*b**	*b** = 4.320 +0.803*A − 0.408*B − 1.045*C − 0.356*A^2 +0.354*B^2 +0.274*C^2 +0.193*AB − 0.098*AC +0.203*BC	0.0207
C*	C* = 4.400 +0.851*A − 0.424*B − 1.065*C − 0.341*A^2 +0.419*B^2 +0.306*C^2 +0.193*AB − 0.090*AC +0.245*BC	0.0194
h°	h° = 74.140 − 1.360*A − 0.200*B − 0.533*C +1.265*A^2 − 0.625*B^2 +1.320*C^2 +0.260*AB − 0.865*AC − 1.660*BC	0.0388
ΔE	ΔE = 56.247 − 1.065*A +1.118*B +3.935*C +0.500*A^2 − 0.470*B^2 − 1.950*C^2 − 0.888*AB +0.952*AC − 1.073*BC	0.0021

A = ET = Extrusion temperature; B = FMC = Feed moisture content; C = HCP/Starch = Huitlacoche/Starch proportion; RT = Residence time; SME = Specific mechanical energy; EI = Expansion index; BD = Bulk density; Tex = Texture; WAI = Water absorption index; WSI = water solubility index; ΔE = total color difference.

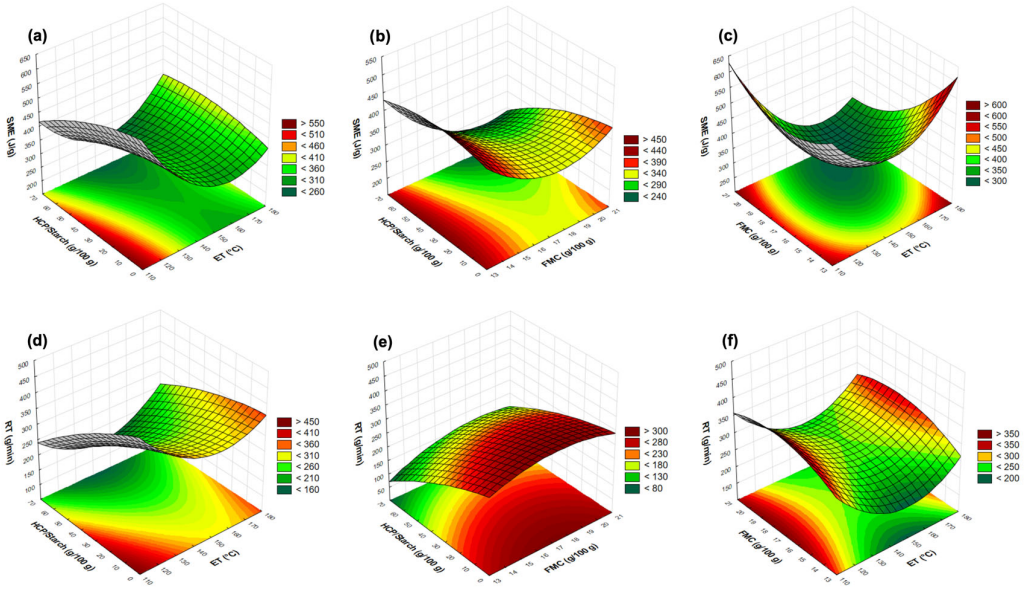


Figure 2. Response surface plot showing the effect of extrusion temperature (ET), feed moisture content (FMC), and Huitlacoche/Starch proportion (HCP/Starch) on (**a**–**c**) specific mechanical energy (SME) and (**d**–**f**) residence time (RT).

3.2. Specific Mechanical Energy (SME)

The SME is a key parameter in extrusion, as it reflects the amount of mechanical energy transferred from the screw to the food matrix during processing. This energy is responsible for starch gelatinization, protein denaturation, fiber solubilization, and other transformations that directly affect expansion, density, texture, and overall quality of extrudates [8,23]. SME values ranged from 271.20 to 525.08 J/g (Table 2). The fitted polynomial model was significant ($p < 0.05$) and explained 91% of the variability ($R^2 = 0.91$), validating its predictive capability (Tables 4 and 5). ET and FMC had negative effects on SME, particularly at low HCP/Starch levels (Figure 2a,b). This behavior is explained by the reduction in melt viscosity and internal friction, which lowers the energy required for material transport [4,5,24]. Similarly, increased FMC significantly reduced SME, which is attributed to the plasticizing effect of water. Lotfi-Shirazi et al. [5] reported similar reductions in barley–carrot pulp blends, where moisture acted as a lubricant, decreasing friction and energy consumption.

The inclusion of huitlacoche also reduced SME (Figure 2c), likely due to a decrease in available starch for gelatinization and an increase in insoluble fiber, which results in a less cohesive mass [25]. This effect has been observed with other functional ingredients such as insect flour [24] or pineapple peel [4]. Similar results have been described by Brennan et al. [7] and Tepsongkroh et al. [10] when using fiber- or fungal protein-rich flours.

From a technological perspective, controlling SME is critical: excessive values may cause thermal degradation and non-enzymatic browning, negatively impacting sensory quality, while insufficient values may lead to incomplete cooking. Therefore, joint optimization of ET, FMC, and HCP/Starch is essential to ensure high-quality functional extruded products.

3.3. Expansion Index (EI), Bulk Density (BD), and Texture (Tex)

The EI is a critical quality parameter in extruded snacks, as it determines product porosity, crispness, and consumer acceptance. High EI values are usually linked with desirable light structure and crunchy texture, while low EI values indicate compact products with high bulk density. Expansion is strongly influenced by extrusion temperature, feed moisture, screw speed, and the presence of proteins and fibers that alter starch gelatinization and

bubble growth [5,8]. EI values ranged from 1.20 to 2.81 (Table 2). The quadratic model fitted for EI was statistically significant ($p < 0.05$), with a determination coefficient of $R^2 = 0.96$ (Tables 4 and 5), indicating excellent predictive capacity. Significant factors affecting this variable included the negative linear effects of FMC and HCP/Starch ratio, as well as the interaction between ET and HCP/Starch (Table 4). As shown in Figure 3a, the highest EI values were obtained at intermediate FMC levels and low proportions of huitlacoche. However, increasing moisture notably reduced EI, due to a lower melt temperature at the die, which limits the sudden evaporation of water and thus expansion [5,14]. Conversely, excessively high temperatures may cause thermal degradation of starch and proteins, reducing their expansion capacity [26].

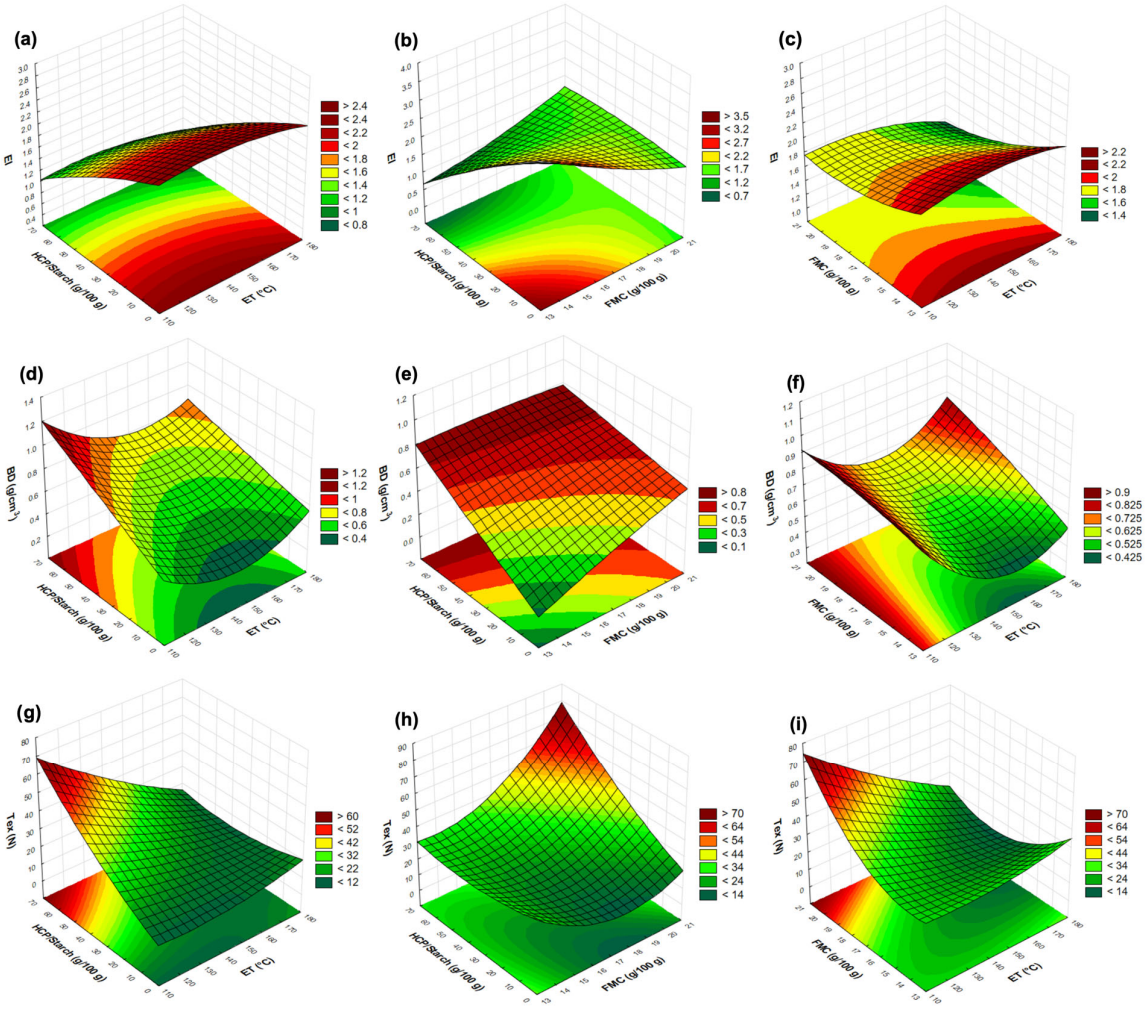


Figure 3. Response surface plot showing the effect of extrusion temperature (ET), feed moisture content (FMC), and Huitlacoche/Starch proportion (HCP/Starch) on (**a**–**c**) expansion index (EI); (**d**–**f**) bulk density (BD); and (**g**–**i**) texture (Tex).

Figure 3b confirms a progressive decrease in EI as the HCP/Starch ratio increases, which is attributed to the high content of insoluble fiber in huitlacoche that interferes with starch gelatinization and limits the expansion of the melt matrix. Additionally, the presence of proteins and phenolic compounds may hinder the stabilization of the cellular structure of the extrudate. The presence of proteins and phenolic compounds interferes with bubble growth and stabilization during expansion. Proteins tend to aggregate under extrusion conditions, increasing melt viscosity, while phenolic compounds interact with starch and proteins through hydrogen bonding, limiting gelatinization and cell wall elasticity, which

reduces uniform expansion [23,27]. This behavior has been documented in blends enriched with insect flour [24] and pineapple peel [4].

The significant ET-HCP/Starch interaction (Figure 3c) suggests that higher temperatures may partially mitigate the negative effect of HCP/Starch on EI by promoting the plasticization of residual starch. However, this recovery is limited and does not fully compensate for the loss in expansion caused by the high fiber content [24,27]. From a consumer perspective, reduced EI typically results in snacks perceived as denser and less crispy, traits associated with lower acceptability in sensory studies [1,9].

The BD is an essential indicator of extrudate structure, directly related to expansion and texture. Low BD values are associated with well-expanded, porous, and crisp products preferred by consumers, whereas high BD reflects compact structures with lower expansion and harder texture. BD is primarily influenced by feed moisture, extrusion temperature, and ingredient composition, as these factors determine starch gelatinization, melt viscosity, and bubble stabilization during extrusion [5,8].

BD values ranged from 0.32 to 0.89 g/cm^3 (Table 2). Regression analysis (Table 4) revealed that the HCP/Starch ratio was the only statistically significant factor, with a positive effect on density. The fitted polynomial model was significant ($p < 0.05$), with $R^2 = 0.71$ (Tables 4 and 5). This implies that higher inclusion of huitlacoche leads to denser products, due to reduced radial expansion caused by insoluble fiber and starch dilution in the mixture [14]. Figure 3d shows a linear increase in BD with increasing HCP/Starch at constant ET and FMC values.

Figure 3e shows that at intermediate temperatures (~145 °C) and moderate moisture (~18–20%), BD slightly decreases, suggesting partial matrix expansion. However, Figure 2f indicates that this effect is counteracted by increasing huitlacoche levels, where density increases again. This pattern has been reported in previous studies with fiber-rich by-products such as pineapple peel, carrot pulp, or insect flour [4,5,24]. Higher BD is associated with snacks that are harder to bite and less aerated, features generally less preferred by consumers in hedonic evaluations [9,10].

Texture, commonly expressed as hardness, is a decisive quality attribute in extruded snacks, as it defines crispness and the sensory perception of crunchiness that directly influences consumer acceptance. A desirable extrudate texture is usually characterized by moderate hardness with a brittle fracture, which depends on expansion, cell wall thickness, and the structural integrity of the matrix. Processing variables such as feed moisture, extrusion temperature, and ingredient composition strongly affect texture through their influence on starch gelatinization and bubble formation [8,27]. The Tex of the extrudates ranged from 12.76 to 59.19 N (Table 2). Significant effects included the negative linear effect of ET, positive linear effects of FMC and HCP/Starch, the quadratic effect of FMC^2, and negative interactions between ET × FMC, ET-HCP/Starch, and FMC-HCP/Starch (Table 4). The fitted model was also highly significant ($p < 0.05$), with $R^2 = 0.94$ (Tables 4 and 5), explaining 94% of the variability. Figure 3g illustrates that hardness decreases with increasing ET, because of enhanced starch gelatinization and the formation of a porous, less resistant structure [27,28]. In contrast, increasing HCP/Starch led to firmer extrudates (Figure 3h), due to the lower proportion of gelatinizable starch and the structuring effect of insoluble fiber, consistent with previous findings in formulations enriched with unconventional ingredients [4,13,24].

Finally, the quadratic effect of FMC^2 (Figure 3i) shows that texture reaches a minimum at intermediate moisture levels (~18–20%), while higher or lower values produce harder extrudates. This behavior is explained by the balance between plasticity, expansion, and water retention in the matrix during processing. Importantly, texture strongly influences consumer preference: extrudates that are excessively hard are often perceived as less

palatable, whereas moderate hardness and crispness are consistently associated with higher acceptance in sensory studies of mushroom- and insect-enriched snacks [1,10].

Overall, these results highlight that EI, BD, and Tex are not only influenced by the HCP/Starch ratio, ET, and FMC, but also directly determine consumer perception and the functional suitability of the product. Optimization of these factors is essential to tailor extrudate structural to achieve desirable crispness, lightness, and overall acceptability in functional snack applications.

3.4. Water Absorption Index (WAI), Water Solubility Index (WSI), and pH

The WAI is an indicator of the ability of extrudates to absorb and retain water, reflecting the degree of starch gelatinization and the integrity of the molecular structure after extrusion. High WAI values are generally desirable in expanded snacks as they denote greater starch modification, which contributes to product porosity and improved texture. This parameter is strongly affected by extrusion temperature, feed moisture, and ingredient composition, since proteins and fibers can either limit or enhance starch swelling depending on their interactions [5,8]. WAI values ranged from 4.15 to 7.07 g/g (Table 2). Significant influencing factors included the positive linear effect of ET, and negative effects from FMC and the HCP/Starch ratio, as well as the ET-FMC interaction (Table 4). The fitted model for the WAI was statistically significant ($p < 0.05$), with a coefficient of determination $R^2 = 0.98$ (Tables 4 and 5), indicating a robust fit to the experimental data. As shown in Figure 4a, WAI significantly decreased with increasing HCP/Starch. This effect is attributed to the lower availability of starch for gelatinization and the reduced water-holding capacity of the insoluble fiber in huitlacoche. Similar findings were reported by Brennan et al. [7], who observed decreases in WAI when incorporating β-glucans and insoluble fiber into barley and mushroom-based extrudates.

Figure 4b shows that WAI decreased at high FMC levels, likely due to lower internal friction and reduced effective barrel temperature, which limits starch gelatinization. Rivera-Mirón et al. [4] documented a similar pattern when using pineapple by-products under high-moisture conditions.

Figure 4c shows that even at intermediate ET levels, the reduction in WAI with increasing HCP/Starch persists, due to the limited water–matrix interaction caused by the high fiber content. While higher temperatures promote starch granule rupture and hydroxyl group exposure [5], excessive temperatures may induce retrogradation or structural reorganization, thereby reducing WAI [26].

The WSI measures the fraction of soluble components released from the extrudate into water, reflecting the degree of starch dextrinization and molecular breakdown during extrusion [6,25]. High WSI values indicate intense macromolecular degradation, which enhances solubility but may compromise structural integrity, while moderate values are associated with desirable functional properties in expanded snacks [5,8]. Values ranged from 8.34 to 22.91% (Table 2). Significant factors included the positive linear effect of FMC and the positive quadratic effect of HCP/Starch^2 (Table 4). The fitted model was also significant ($p < 0.05$), with $R^2 = 0.86$ (Tables 4 and 5). Figure 4d shows an increase in WSI with the HCP/Starch ratio, particularly under low ET conditions. This behavior may be explained by the presence of soluble compounds (mainly β-glucans and heteropolysaccharides) in huitlacoche, such as non-starch polysaccharides, proteins, and polyphenols, which may solubilize or fragment during thermal processing. Comparable results were reported by Brennan et al. [7], who observed that the incorporation of mushroom powders into extruded corn-based snacks increased solubility due to the release of low molecular weight compounds during extrusion. Similarly, Lotfi-Shirazi et al. [5] reported higher WSI values in barley-carrot pomace extrudates, associated with fiber depolymerization

under high shear conditions. However, in our study, the effect of the HCP/Starch ratio was more pronounced at low ET, suggesting that huitlacoche-derived components are more sensitive to thermal degradation than cereal fibers [6,25]. These differences highlight that the nature of the added ingredient-fungal biomass vs. vegetable fiber-modulates the extent and conditions under which solubilization occurs.

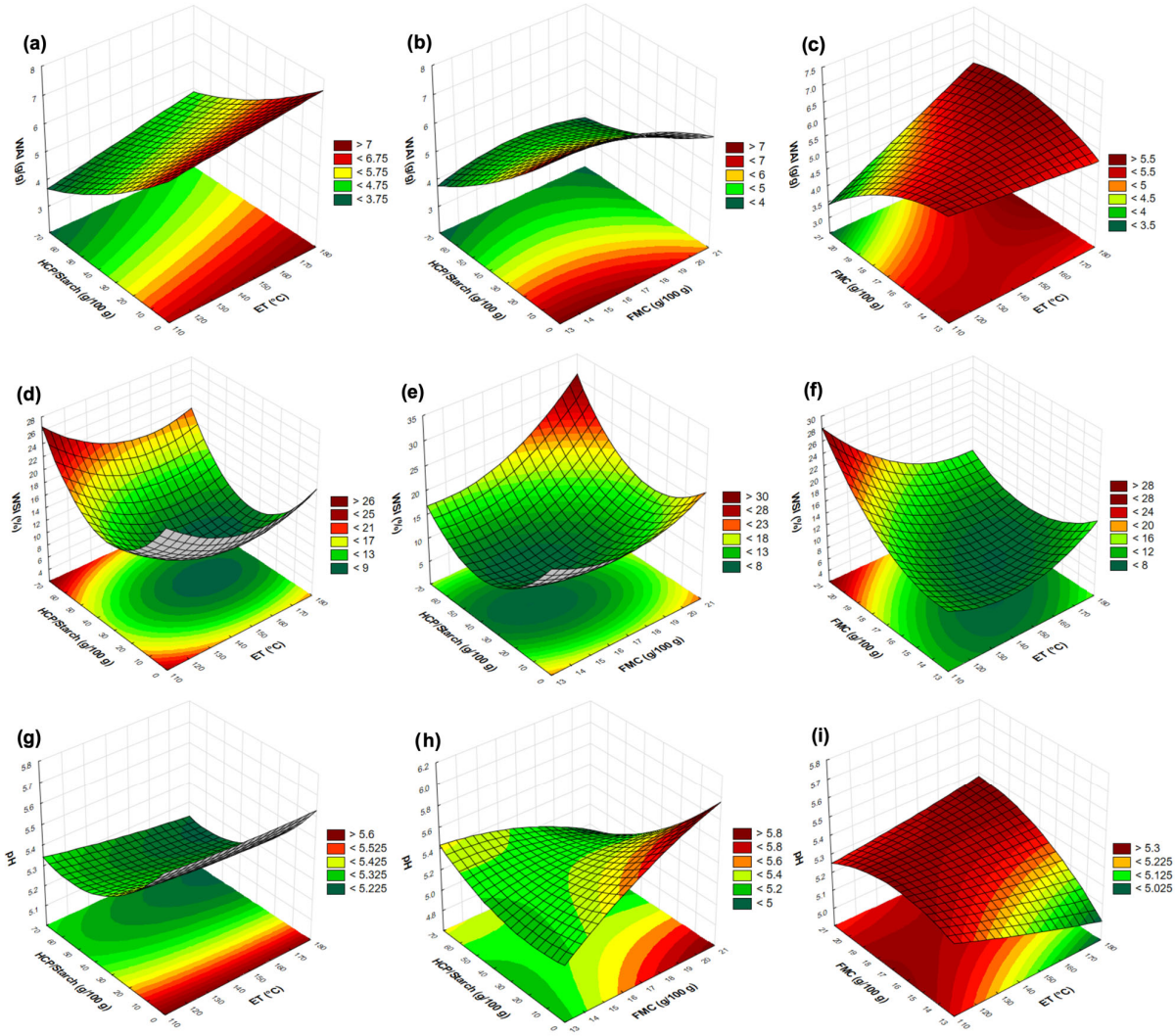


Figure 4. Response surface plot showing the effect of extrusion temperature (ET), feed moisture content (FMC), and Huitlacoche/Starch proportion (HCP/Starch) on (**a**–**c**) water absorption index (WAI); (**d**–**f**) water solubility index (WSI); and (**g**–**i**) pH.

Figure 4e reveals a quadratic relationship between FMC and WSI. At intermediate moisture levels (~20%), melt plasticity favors macromolecular fragmentation and solubilization of components, whereas this effect diminishes at extreme moisture levels. Lotfi-Shirazi et al. [5] described a similar trend in barley–carrot extrudates.

Figure 4f confirms a synergistic interaction between FMC and HCP/Starch: in blends with high huitlacoche content, increased moisture enhances solubility. This is related to the matrix's limited gelation capacity and an increase in non-starch soluble fractions. However, as starch proportion decreases, the potential for depolymerization also declines, which may limit WSI in certain ranges. This phenomenon has been corroborated in extrudates containing insect flours or plant-based by-products [17,24].

The pH of extrudates is an important quality attribute because it influences flavor stability, microbial safety, and the functional behavior of proteins and starch. Changes

in pH during extrusion may result from Maillard reactions, protein denaturation, and the release of acidic or basic compounds. Maintaining pH within an acceptable range is relevant for consumer acceptance and for ensuring the nutritional and functional integrity of extruded products [8,27]. Values ranged from 5.05 to 5.71 (Table 2). Significant factors included FMC (positive), HCP/Starch (negative), the quadratic term HCP/Starch^2, and the FMC–HCP/Starch interaction (Table 4). The adjusted model was statistically significant ($p < 0.05$), with $R^2 = 0.97$ (Tables 4 and 5).

Figure 4g shows a progressive decrease in pH with increasing HCP/Starch, attributed to the mildly acidic nature of huitlacoche, which contains organic acids and phenolic compounds derived from fungal metabolism. Téllez-Morales et al. [23] and Brennan et al. [7] also reported a pH reduction in extruded blends containing fungal and fermented plant flours. Figure 4h,i indicate that ET and FMC, in isolation, did not significantly affect pH within the studied ranges, although slight variations were observed due to interactions with HCP/Starch.

The WAI, WSI, and pH results reveal that huitlacoche significantly modifies the functional and hydrophilic properties of extrudates. These changes must be carefully considered during product design, particularly for functional, instant, or application-specific extruded foods requiring defined stability and solubility properties.

3.5. Color Parameters (L, a*, b*, C*, h°, and ΔE)*

Color is a key quality attribute in extruded snacks because it directly influences consumer perception and acceptability. These attributes are strongly affected by extrusion temperature, feed moisture, and the incorporation of functional ingredients, as pigments, proteins, and phenolic compounds undergo thermal degradation and Maillard reactions during extrusion [5,8]. *L** values ranged from 39.94 to 51.98 (Table 3). The polynomial model fitted for *L** was statistically significant ($p < 0.05$), with a determination coefficient of $R^2 = 0.98$ (Tables 4 and 5), indicating a high explanatory power According to Table 3, significant effects on *L** included a positive effect from ET and negative effects from FMC and HCP/Starch, as well as from HCP/Starch^2 and the FMC–HCP/Starch interaction. This suggests that increasing the proportion of huitlacoche in the blend decreases product lightness, making it visually darker.

Figure 5a shows that, at constant HCP/Starch, the ET–FMC interaction leads to relatively stable *L** values, with slight decreases at high temperatures. However, Figure 4b reveals a clear reduction in *L** with increasing HCP/Starch, regardless of ET. This is attributed to the presence of dark pigments such as melanins, and to the higher thermal reactivity of phenolic compounds and proteins in huitlacoche, which intensify non-enzymatic browning [25]. Figure 5c confirms that this effect remains consistent across FMC levels. These findings are consistent with those reported by Téllez-Morales et al. [24] and Rivera-Mirón et al. [4], who observed similar *L** reductions when incorporating dark flours such as cricket meal or pigmented by-products.

From a technological and market perspective, reduced lightness may be favorable in snack products with barbecue or chili flavors, where darker hues are visually acceptable or even preferred. However, in products where visual clarity is expected, this darkening may pose a limitation.

The fitted model for *a** was also significant ($p < 0.05$), with $R^2 = 0.95$ (Tables 4 and 5). *a** values ranged from 0.52 to 1.58 (Table 3), indicating reddish tones across all treatments. Significant effects included: ET (positive), FMC and HCP/Starch (negative), and the FMC–HCP/Starch interaction (Table 4). Figure 5d shows that, at constant HCP/Starch, neither ET nor FMC significantly affects *a**. However, Figure 5e shows a consistent decrease in *a** with increasing huitlacoche, attributed to the neutralization of red tones by the dark pigments of the fungus. This trend is also visible in Figure 5f, where FMC

does not substantially alter the effect of huitlacoche. Similar results were reported by Téllez-Morales et al. [24] and Rivera-Mirón et al. [4].

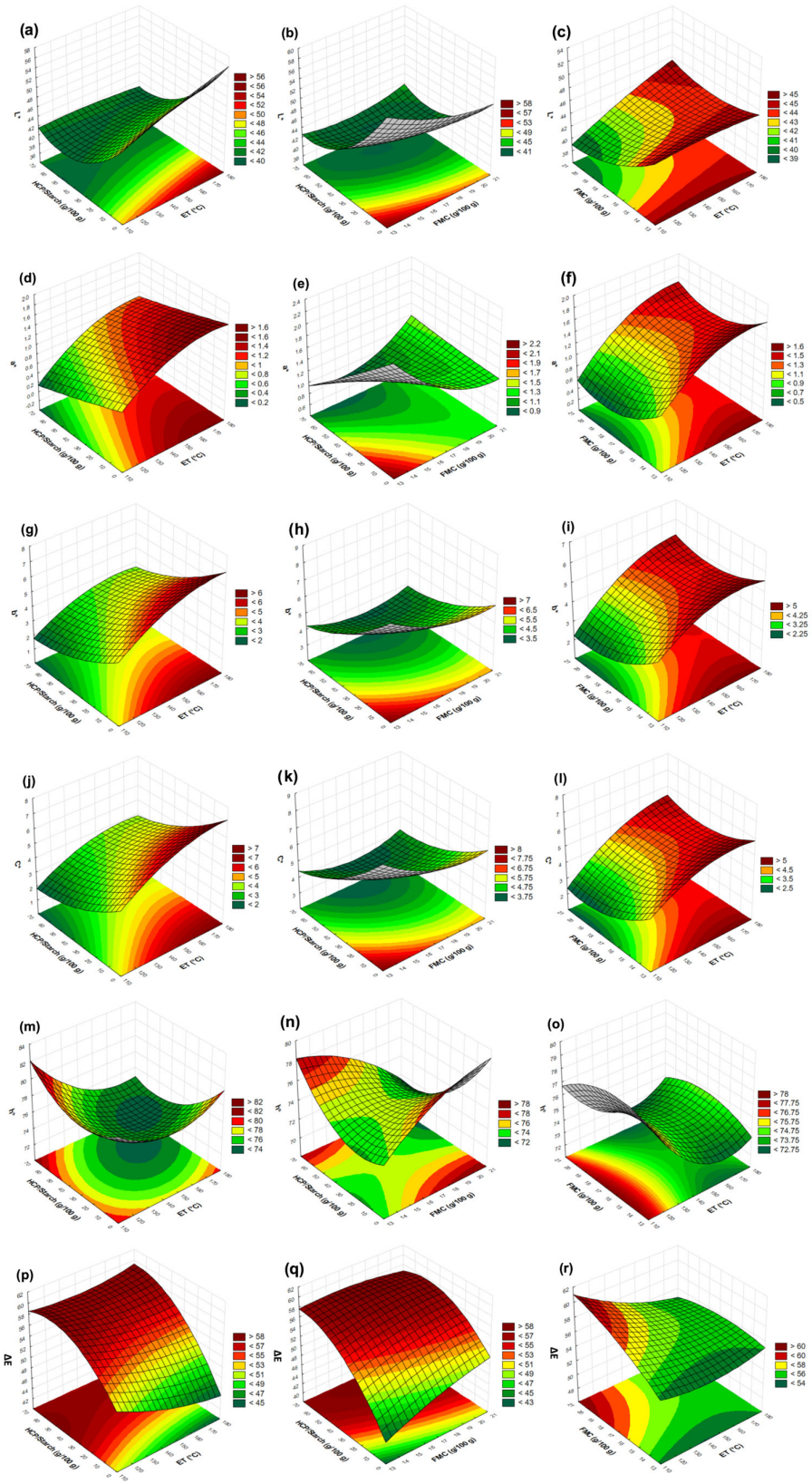


Figure 5. Response surface plot showing the effect of extrusion temperature (ET), feed moisture content (FMC) and Huitlacoche/Starch proportion (HCP/Starch) on color parameters: (**a**–**c**) *L**; (**d**–**f**) *a**; (**g**–**i**) *b**; (**j**–**l**) C*; (**m**–**o**) h°; and (**p**–**r**) total color difference (ΔE).

For the b^* component, b^* values ranged from 2.72 to 6.71 (Table 3), representing noticeable yellow tones. The quadratic model was significant ($p < 0.05$) with $R^2 = 0.93$ (Tables 4 and 5). ET had a positive effect and HCP/Starch a negative effect. Figure 5g indicates that increasing ET intensifies yellow coloration, likely due to the formation of Maillard pigments. Figure 4h shows that b^* decreases as HCP/Starch increases, which is explained by carotenoid dilution and incorporation of dark pigments. Figure 4i confirms that this trend persists across all FMC levels. Similar patterns have been reported in studies using pigmented ingredients such as pineapple peel or cricket flour [4,24].

The model fitted for C* (chroma) was also significant ($p < 0.05$), with $R^2 = 0.93$. ET showed a positive effect, and HCP/Starch a negative one. Values ranged from 2.82 to 6.97 (Table 3). Figure 5j shows that C* increases with ET at low huitlacoche proportions, whereas Figure 5k shows a steady decline in C* as HCP/Starch increases. In Figure 5l, ET increases chroma even with FMC variations. This suggests a shift toward less saturated and duller tones, as observed in previous studies involving dark functional ingredients [7,24].

For h°, the model was statistically significant ($p < 0.05$), with $R^2 = 0.91$. ET had a negative effect, HCP/Starch^2, a positive effect, and FMC–HCP/Starch interaction, a negative effect. The decrease in h° with ET indicates a shift toward orange tones, likely due to Maillard reactions and thermal degradation of pigments [29]. Figure 5n shows two zones with high h° values: one at high FMC and another at low HCP/Starch, reflecting a dual modulation between moisture and huitlacoche ratio. Figure 5o indicates that low ET helps preserve high h° values. This behavior aligns with findings from Sudhakar et al. [17] and Tepsongkroh et al. [10] in extruded mushroom-based products.

Lastly, the model for ΔE was highly significant ($p < 0.05$), with $R^2 = 0.97$. Significant variables included FMC and HCP/Starch (positive), ET (negative), and HCP/Starch^2. Figure 5p,q show that increasing huitlacoche sharply raises ΔE, indicating a noticeable color change. Figure 5r confirms that this shift remains consistent regardless of moisture level. This behavior, also reported by Téllez-Morales et al. [24], Tangsrianugul et al. [14], and Brennan et al. [27], suggests that final product color is highly dependent on formulation. From a functional and marketing standpoint, high ΔE values may be acceptable or desirable in functional formulations. However, if visual similarity to traditional products is required, strategies such as color stabilization or formulation adjustments should be implemented.

3.6. Optimal Condition for the Extruded Product

The multi-response optimization of the extrusion process, performed using RSM via Design-Expert® software, enabled the identification of ideal conditions to maximize the physicochemical and functional quality of a huitlacoche-enriched extruded snack. The optimization criteria simultaneously aimed to maximize the EI and minimize BD, Tex, and SME, while ensuring values within acceptable ranges for techno-functional properties (WAI, WSI), pH, and color parameters (L^*, a^*, b^*, C*, h°, ΔE) (Table 6).

Three optimal conditions were identified with ET values of 149.85, 150.15, and 150.38 °C; FMC values of 15.71, 15.76, and 15.80 g/100 g; and HCP/Starch ratios of 10, 15, and 20 g/100 g, respectively. These combinations yielded global desirability values of 0.88, 0.85, and 0.83, respectively. In the context of multi-response optimization, desirability values above 0.80 are typically considered indicative of high-quality products with acceptable trade-offs between responses. This suggests that the optimized formulations not only achieved statistical robustness but also reached thresholds consistent with consumer acceptability reported in extrudates enriched with non-conventional ingredients [4,7]. These values are comparable to or even higher than those reported in similar extrusion studies using fiber-rich vegetable by-products, such as pineapple peel [4] and carrot pulp [5].

Table 6. Optimum values of extrusion process parameters and responses for extruded snack.

Process Parameters	Importance	Target	Experimental Range		Optimum Value		
			Min	Max			
ET (°C)	3	Range	120	170	149.85	150.15	150.38
FMC (g/100 g)	3	Range	14	20	15.71	15.76	15.80
HCP/Starch (g/100 g)	5	Range	10	60	10.00	15.00	20.00
Responses					Predicted values		
RT (g/min)	3	Range	188.76	438.83	297.30	288.70	279.43
SME (J/g)	5	Minimize	271.2	525.08	347.03	347.80	347.62
EI	5	Maximize	1.05	2.81	2.52	2.40	2.27
BD (g/cm^3)	5	Minimize	0.31	1.13	0.32	0.36	0.40
Tex (N)	5	Minimize	12.76	59.19	17.53	17.42	17.51
WAI (g/g)	3	Range	4.13	7.07	6.91	6.61	6.34
WSI (%)	3	Range	8.34	22.91	12.99	11.16	9.74
pH	3	Range	5.05	5.71	5.54	5.36	5.33
*L**	3	Range	39.94	51.98	50.54	48.74	47.12
*a**	3	Range	0.52	1.90	1.60	1.53	1.47
*b**	3	Range	2.72	6.71	6.11	5.78	5.47
C*	3	Range	2.82	6.97	6.29	5.94	5.61
h°	3	Range	72.14	79.43	75.18	74.73	74.37
ΔE	3	Range	47.92	59.52	49.04	50.67	52.15
Desirability					0.88	0.85	0.83

ET = Extrusion temperature; FMC = Feed moisture content; HCP/Starch = Huitlacoche/Starch proportion; RT = Residence time; SME = Specific mechanical energy; EI = Expansion index; BD = Bulk density; Tex = Texture; WAI = Water absorption index; WSI = Water solubility index; ΔE = total color difference.

The predicted responses under these optimal conditions included an EI of 2.27, associated with a low BD (0.40 g/cm^3) and intermediate texture (17.51 N), key attributes for crunchy snacks. The estimated SME (347.62 J/g) suggests acceptable energy efficiency, consistent with extrusion processes involving starch–plant protein blends [23,29].

From a functional perspective, appropriate values of WAI (6.34 g/g) and WSI (9.74%) were obtained, reflecting partial starch gelatinization and the formation of a matrix with moderate water absorption and release capacity, properties relevant for sensory acceptance and preparation practices. The pH (5.33) remained within a slightly acidic range, attributable to the phenolic compounds in huitlacoche, without compromising the physicochemical stability.

In terms of color, a slight decrease in lightness (*L** = 47.12) and chroma (C* = 5.61) was observed, accompanied by a moderate yellow-reddish hue (h° = 74.37°) and a perceptible but visually acceptable total color difference (ΔE = 52.15). While these changes highlight the trade-off between nutritional enrichment and color uniformity, they remain within the range of consumer-acceptable values for pigmented snacks such as cricket- or legume-based extrudates [24,27].

Overall, the optimization approach proved effective in balancing multiple quality responses, as reflected in the high desirability values (>0.80), which confirm the feasibility of designing huitlacoche-based extrudates with suitable expansion, texture, and functional properties, even when minor compromises in color are present. These results reinforce the applicability of the approach for industrial-scale processes and the development of functional foods using underutilized traditional ingredients such as huitlacoche. Nevertheless, further studies are needed to assess the impact of extrusion on nutraceutical properties (e.g., antioxidant capacity) and to conduct sensory acceptability tests that validate the commercial potential of the optimized product.

4. Conclusions

This study demonstrated the technical feasibility of incorporating huitlacoche (*U. maydis*) as a functional ingredient in the formulation of corn starch-based extruded products, using RSM and a single-screw extruder to identify optimal conditions. ET, FMC, and the HCP/Starch ratio significantly influenced EI, BD, Tex, SME, and color parameters. Moderate levels of huitlacoche (up to 20 g/100 g), combined with optimal extrusion conditions (150.38 °C and 15.80 g/100 g FMC), produced snacks with high expansion, low BD, crunchy texture, suitable techno-functional properties (WAI and WSI), and visually acceptable color, achieving global desirability values between 0.83 and 0.88. C* and ΔE were particularly sensitive to huitlacoche inclusion, while h° remained relatively stable. Beyond these technical findings, this research contributes to the valorization of huitlacoche as an underutilized traditional ingredient, demonstrating its potential to diversify the portfolio of functional extruded snacks and to enhance the industrial use of agro-food resources with cultural and nutritional value. The optimization approach confirms its applicability in industrial-scale extrusion processes, offering a pathway for developing innovative, health-oriented products. Future research should evaluate sensory acceptability, storage stability, and the retention of bioactive compounds during processing and shelf life to validate both the functional and commercial potential of huitlacoche-based extruded foods.

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Abbreviations

The following abbreviations are used in this manuscript:

BD	Bulk density
EI	Expansion index
ET	Extrusion temperature
HCP/Starch	Huitlacoche/Starch proportion
MCF	Feed moisture content
RT	Residence time
SME	Specific mechanical energy
Tex	Texture
WAI	Water absorption index
WSI	Water solubility index
ΔE	Total color difference

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