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Research article

Physicochemical and sensory functions of rice-based third-generation snacks enriched with chickpea and red pitaya powder

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Abstract: The present study evaluated the incorporation of red pitaya powder into a rice/chickpea (80:20) matrix, resulting in four treatments, namely T-2.5 (2.5%), T-5.0 (5.0%), T-7.5 (7.5%), and T-10 (10%) powder addition, which were processed through extrusion cooking, followed by microwave expansion for the development of a third-generation (3G) snack. The physicochemical properties, including expansion index (EI), hardness, and bulk density (BD), as well as functional parameters such as total polyphenol content (TPC) and antioxidant activity (AA), were analyzed. Furthermore, structural modifications generated by processing were examined via X-ray diffraction, FT-IR spectroscopy, and microstructural analyses. The addition of pitaya powder significantly affected the physicochemical properties of the 3G snacks, resulting in a decrease in EI, BD, and hardness after the extrusion and expansion process using microwaves. In addition, the bioactive potential of the snacks improved, generating the highest levels with the addition of pitaya powder, resulting in a 38% increase in TPC and a 3.1-times increase in AA, with a retention of 30% in total betalain content (TBC). Microstructural analyses showed modifications after processing, with a loss of crystalline order and transitions in the type-V diffraction pattern, indicative of amylose–lipid complex formation, characterized by a decrease in the 1047/1022 ratio and stability of 1022/995 ratio. Also, the sensory analysis revealed that the 7.5% formulation was the most attractive, maintaining the principal characteristics of color and texture, with a general acceptance above 38%. These results demonstrate that the incorporation of pitaya powder enhances the bioactive, functional, and sensorial properties of third-generation extruded products.

Keywords: bioactive compounds; chickpea; extrusion; powder red pitaya; sensory evaluation; third-generation snacks

1. Introduction

In recent years, snack consumption has become increasingly linked to health and wellness trends, as consumers seek products that not only offer convenience and sensory appeal but also provide nutritional and functional benefits while avoiding artificial additives and synthetic colorants [1,2]. Consequently, there is a demand for functional ingredients derived from natural, healthy alternatives to conventional snacks, such as mixtures of cereals and legumes, such as rice and chickpea, due to their nutritional composition. Rice provides easily digestible carbohydrates, neutral flavor, low allergenicity, and excellent expansion behavior. In contrast, chickpeas contain high-quality proteins, dietary fiber, bioactive compounds with biological activities, and micronutrients, being a source of fatty acids, such as oleic and linoleic acids [3–5]. Furthermore, chickpeas are thermally stable and have a high water-absorption capacity, which may make them suitable for use in the snack manufacturing process. In addition, their combination also provides a nutritionally complete combination of essential amino acids [4,5].

Despite this shift toward healthier alternatives, many traditional snacks, such as potato chips, flavored popcorn, corn chips, and crackers, remain high in calories, glycemic indices, and sodium. Frequent or excessive consumption of these products has been linked to an increased risk of obesity, hypertension, insulin resistance, and cardiovascular diseases, underscoring their significance as public health concerns and challenges for the food industry [1,6]. Despite their nutritional benefits, consumers also value the visual appearance of products, which is why the use of artificial colors is a common practice in the food industry. However, synthetic coloring raises concerns regarding both health and consumer perception. Several studies have linked them to adverse effects such as hyperactivity in children, allergic reactions, and potential long-term health risks, which has driven a growing interest in natural alternatives that maintain visual appeal without compromising product safety or nutritional quality [1,7]. Therefore, natural colorants derived from fruits, vegetables, and spices provide safer alternatives for consumers. Among the primary pigments are anthocyanins (red, purple, or blue), which are found in berries, grapes, and red cabbage [8]; carotenoids, which are yellow to orange pigments, including β-carotene, lycopene and lutein, that are present in papaya, carrot, sweet potato, tomato, and oranges [7–9]; and betalains, which are red to violet (betacyanins) and yellow to orange (betaxanthins) pigments and are found in beets (*Beta vulgaris* L. var. *conditiva* Alef.), pitaya [*Stenocereus thurberi* (Engelm.) Buxb], pitahaya [*Hylocereus undatus* (Haw.) Britton and Rose], and Swiss chards (*Beta vulgaris* L. var. *cicla* L.). These pigments help neutralize free radicals, offering potential anti-inflammatory and anticancer properties [9–11]. However, they also present limitations, such as sensitivity to heat, light, and pH, which may compromise product stability and appearance [10–12]. To improve the stability of bioactive compounds and ensure their functionality in food products, spray drying is a highly effective preservation and protection technique. This process enables the encapsulation of the pigments, creating a physical barrier that minimizes degradation caused by light, oxygen, heat, and pH changes. In addition to prolonging shelf life, it preserves the color and antioxidant properties of bioactive compounds [10,11].

Third-generation (3G) snacks are produced through the extrusion process, which enables the integration of innovative processing techniques with enhanced nutritional properties [12,13]. This technology subjects the food matrix to moderate temperatures and shear forces, compared to those used for expanded extruded products, generating structural changes in macromolecules, particularly starch and proteins [13,14]. As such, it is of interest to evaluate the impact of extrusion cooking on the physical and chemical characteristics of extrudates for the development of 3G snacks. The development of 3G snacks based on rice and chicken peas represents a healthy alternative to conventional snacks, providing high-quality proteins, fiber, and bioactive compounds. Several studies report the development of extruded cereal products enriched with plant bioactives. Igual et al. [14] showed that beetroot powder improves color, antioxidant capacity, and expansion of microwave-expanded 3G snacks, and Kojić et al. [15] reported that the incorporation of betaines does not increase bitterness and produces sensorially acceptable products. Similarly, Acurio et al. [12] and Kantrong et al. [16] demonstrated that anthocyanin-rich flours enhance expansion, texture, and functional properties in 3G snacks. Unlike previous studies that used individual ingredients, such as cereals and legumes, this study includes ingredients that can improve the nutritional and bioactive profile of the final product, including powder pigments such as betalains. The development of these 3G snacks, which combine rice and chickpea with a red pitaya pigment, represents a promising strategy to enhance the nutritional and functional benefits in response to current consumer demand for color, bioactive, and plant-based products. However, research on the incorporation of red pitaya powder in rice and chickpea mixtures for 3G snacks is limited. Therefore, determining how the incorporation of pitaya powder affects the structural, physicochemical, and functional properties of 3G snacks is essential to achieving optimized formulations with desired quality characteristics. The objective of this study was to evaluate the impact of adding pitaya powder on the physicochemical, sensory, and textural properties of 3G snacks produced by extrusion and expanded through microwave heating.

2. Materials and methods

2.1. Raw material

White rice (*Oryza sativa* L.) and chickpea (*Cicer arietinum* L.) were acquired commercially in the local market "Central de abastos" in Chihuahua, Mexico. Mexican red pitaya [*Stenocereus thurberi*] was collected from the Sirebampo community in Sonora State, Mexico (26°38'20.7"N, 109°14'42.5"W). This cactus grows wild in the region. The local climate is characterized by an average maximum temperature of 31.3 °C, a minimum of 13.5 °C, and an annual precipitation of 558.1 mm. Pitaya juice with a 12.2% soluble solids content was used to obtain pitaya powder via spray drying, according to Neder-Suarez et al. [17]. Maltodextrin was used as the wall material at a concentration of 30%, and the drying process was carried out in a laboratory-scale spray dryer (Yamato ADL311S, Yamato Scientific, Tokyo, Japan), at a process temperature of 150 °C, an outlet temperature of 70 °C, a solution feed rate of 10 mL/min, an atomizing pressure of 0.1 MPa, and a spray nozzle diameter of 711 µm. The resulting powder was stored in hermetic glass bottles at 4 °C in the dark until use.

2.2. Chemical materials

Folin–Ciocalteu phenol, Trolox, and DPPH were acquired from Sigma–Aldrich. Sodium carbonate, gallic acid, methanol, and hydrochloric acid were obtained from J.T. Baker.

2.3. Flour preparation for extrusion cooking

White rice and chickpea were ground using an SK 100 cutting mill with a 0.5-mm screen and sieved through a 400-µm USA standard test sieve to ensure a uniform particle size. The base mixture was prepared with an 80:20 rice/chickpea proportion. Four treatments were generated for the study: T-2.5 (2.5% addition of pitaya powder), T-5.0 (5.0%), T-7.5 (7.5%), and T-10 (10%). Each treatment was conditioned to 24% moisture content and stored in polyethylene bags at 4 °C for 12 h for stabilization.

2.4. Extrusion cooking process

The extrusion mixtures were processed using a single-screw extruder (Brabender CWB, model 2523). The feed rate was 41.3 g/min, with barrel temperatures set at 80 °C (feed zone), 155 °C (cooking zone), and 90 °C (final zone), and a screw speed of 30 rpm. A circular die with a 2 mm opening was used. The pellets were air-dried at 25 °C for 24 h. The pellets were expanded via microwave heating with a Hamilton Beach (model HB-P70B20AP-SC) at 700 W, according to the method of Neder-Suarez et al. [18]. Different cooking times of 17, 20, 23, 26, 29, 32, and 35 s were used to determine the maximum expansion. The results indicated that the pellets had the best expansion characteristics at 23 s of cooking time, as after 26 s, they showed brown coloration and signs of burning. One portion was stored as pellets, while the other portion was milled, sieved (250 µm), and stored at 4 °C.

2.5. Physicochemical properties

The expansion index (EI) and bulk density (BD) were measured according to Zambrano et al. [19]. EI was evaluated on pellets approximately 40 mm in length by taking three measurements with a digital vernier caliper at three points along the cross-section. Bulk density (BD) was calculated using the following Eq (1):

$$BD = \frac{Weight}{\pi \ x \left(\frac{d}{2}\right)^2 x \ L} \tag{1}$$

where d = diameter, and L = length of the pellets. BD was reported as kg/cm^3. The results represent the average of 20 measurements ± standard deviation.

2.5.1. Texture

The hardness of the pellet and expanded snack samples was measured via a TA/XT2 texture analyzer following Zambrano et al. [19] with modifications. The samples (40 mm) were placed on a base with 25 mm between supports and compressed for 10 mm using a flat blade (TA-43). The pretest, test, and posttest speeds were 0.5, 0.5, and 5 mm/s, respectively. The results represent the average of 20 measurements ± standard deviation.

2.6. Chemical properties

2.6.1. Extract preparation

Extracts for antioxidant activity (AA), total polyphenol content (TPC), and total betalain content (TBC) were prepared on the basis of Soto-Dagnino et al. [20] with slight modifications. For TPC and AA, 1.0 g of sample was mixed with 5 mL of methanol, sonicated for 20 min at 25 °C (Branson 1800, USA), and centrifuged at 3000 × *g* for 10 min (Sorvall ST 8R, Thermo Fisher, USA). For TBC, 1.0 g of sample was extracted with 10 mL of deionized water under the same conditions. The supernatants were filtered through 0.45 μm nylon membranes (Millipore, USA) and centrifuged at 11750 × *g* for 15 min (Hermle Z167 M, Labortechnik GmbH, Germany) before analysis.

2.6.2. Total polyphenol content

The total polyphenol content was determined via a modified Folin–Ciocalteu colorimetric method. 100 μL of sample extract was mixed with 50 μL of Folin reagent and 3 mL of distilled water. After a 10-min incubation, 400 μL of sodium carbonate solution (7.5%) was added. The absorbance was recorded at 760 nm via a Genesys 50 UV/VIS spectrophotometer (Thermo Fisher Scientific, MA, USA). TPC was calculated using Eq (2), and the results are expressed as milligrams of gallic acid equivalents per 100 g of sample (mg GAE/100 g).

$$TPC = \frac{C*Vd}{Wd} \tag{2}$$

where C is the concentration of gallic acid equivalents (500–1000), Vd is the extract volume (mL), and Wd is the weight of the sample (g).

2.6.3. Antioxidant activity

AA was determined by the DPPH free radical. The reaction was conducted by mixing 0.1 mL of extract with 3.9 mL of DPPH (100 μM) after 3 h at 25 °C in the dark. The absorbance was measured at 517 nm (Genesys 50 UV/VIS, Thermo Fisher Scientific, MA, USA). AA was calculated using Eq (3), and the results are reported as μmol Trolox equivalents/100 g.

$$AA = \frac{C*Vd}{Wd} \tag{3}$$

where C is the concentration of μmol Trolox equivalents (0.1–1.2), Vd is the extract volume (mL), and Wd is the weight of the sample (g).

2.6.4. Betalain quantification

The total betalain content was measured via a Genesys 50 UV/VIS spectrophotometer (Thermo Fisher Scientific, MA, USA) according to Soto-Dagnino et al. [20]. The results are expressed as the total TB = betalain content (mg/g d.b. sample) and were calculated from the sum of the BC = total betacyanin content and BX = total betaxanthin content. BC and BX were calculated using the following Eq (4).

$$BC\ \ and\ \ BX = \left(A*\ \ DF*\ \ Mw*\ \left(\frac{Vd}{\varepsilon LWd}\right)\right) \tag{4}$$

where A is the absorbance for betacyanins (535 nm) and betaxanthins (483 nm). DF is the dilution factor, Vd is the extract volume (mL), Wd is the weight of the sample (g), and L is the cell path length (1 cm). Betanin (Mw = 550 g/mol; ε = 60000 L/[mol·cm] and indicaxanthin I (Mw = 308 g/mol; ε = 48000 L/[mol·cm] were used for betacyanin and betaxanthin quantification.

2.7. Color parameters

The color parameters (L*, a*, b*) of extruded and microwave-expanded pellets were measured via a colorimeter (CR-400/410 Minolta, Osaka, Japan). The samples, milled and sieved to a size smaller than 400 µm, were placed in transparent plastic containers with a 5 cm diameter on a white background. The values represent the average of ten measurements per treatment.

2.8. X-ray analysis

X-ray diffractograms of mixed, extruded, and microwave-expanded samples were obtained via a Panalytical X'Pert Pro MRD (Malvern, U.K.). The data were collected from 5° to 30° (2θ) at a step size of $0.5°\cdot s^{-1}$ and analyzed with OriginPro 9.0 software.

2.9. FT-IR analysis

FT-IR spectra of the mixture, extrudate, and microwave-expanded samples were recorded via an ATR-FTIR spectrometer (PerkinElmer, Norwalk, USA) over the 4000–650 cm^{-1} range, with a resolution of 4 cm^{-1} and ten scans per sample.

2.10. Scanning electron microscopy

SEM analysis was performed on the raw materials, mixtures, extrudates, and microwave-expanded samples via a JSM-5800LV microscope (JEOL, Japan) operated at 10 kV with a secondary electron detector. The samples were gold-coated under high vacuum (Desk II, Denton), and the particle size and morphology were determined via ImageJ software version 1.50i (NIH, USA).

2.11. Sensory study

The sensory evaluation of third-generation snacks was conducted using hedonic testing, following the methodology described by Pęksa et al. [21]. A total of 50 participants, including both males and females, aged 18–40 years, participated in the study. Overall acceptability was assessed via a 5-point scale, where 1 represented the lowest level of acceptance and five the highest. The evaluated sensory attributes included color, hardness, flavor, smell, and crunchiness.

2.12. Experimental design and statistical analysis

A duplicate univariate factorial design was used. The independent variable corresponds to the concentration of pitaya powder added, generating four mixtures: T-2.5 (2.5% addition), T-5.0 (5.0%), T-7.5 (7.5%), and T-10 (10%), as well as a control (80:20 proportion of rice and chickpea). The data were analyzed via ANOVA and Pearson's correlation ($p < 0.05$) via Minitab® 17.1.0 (Minitab Inc., State College, PA, USA). Differences were considered statistically significant at $p < 0.05$ according to Tukey's test.

3. Results and discussion

3.1. Expansion index (EI) and bulk density (BD)

The expansion index (EI) is a key indicator of the structural development of extruded and microwave-expanded snacks. The EI of the extruded products significantly decreased ($p < 0.05$) as the pitaya powder concentration increased (Table 1). The control sample presented the highest EI, whereas the 10% pitaya formulation presented the lowest (Figure 1). This reduction in expansion capacity can be attributed to the higher levels of fibers and sugars from pitaya powder, which limit starch gelatinization and reduce bubble formation during extrusion. Similar effects have been reported by Altaf et al. [22] and Ding et al. [23], who reported that the addition of starch-free components decreases expansion due to a lower starch content and weaker matrix elasticity. After microwave expansion, the EI values increased for all the treatments compared to the extruded products, reflecting the typical behavior of third-generation snacks. The EI was not significantly different ($p > 0.05$) between the control treatment and the 2.5% pitaya treatment, whereas the 10% pitaya treatment resulted in the lowest expansion (Table 1). The increase in EI leads to the development of pores during microwave heating, which in turn increases the pellet radius [13,16,17].

Table 1. Physical parameters of extruded and expanded 3G snacks with the addition of pitaya powder.

AP (%)	Extruded products			Microwave-expanded products		
	EI	DB (kg/cm^3)	Hardness (N)	EI	DB (kg/cm^3)	Hardness (N)
2.5	4.89 ± 0.27^{a}	327.95 ± 6.21^{b}	28.49 ± 2.43^{a}	8.94 ± 0.23^{a}	57.87 ± 2.05^{c}	5.96 ± 1.06^{ab}
5	4.56 ± 0.09^{b}	323.23 ± 8.33^{bc}	26.26 ± 1.73^{b}	8.78 ± 0.31^{a}	60.81 ± 2.27^{c}	4.87 ± 1.59^{bc}
7.5	4.54 ± 0.10^{b}	315.00 ± 5.34^{cd}	19.70 ± 2.38^{c}	8.32 ± 0.32^{b}	67.84 ± 6.61^{b}	4.56 ± 0.84^{cd}
10	4.46 ± 0.09^{b}	310.46 ± 5.17^{d}	16.81 ± 2.30^{d}	7.66 ± 0.24^{c}	75.34 ± 2.44^{a}	3.63 ± 1.28^{d}
Control	5.17 ± 0.29^{a}	376.36 ± 16.86^{a}	29.42 ± 2.09^{a}	9.23 ± 0.31^{a}	40.84 ± 6.17^{d}	6.12 ± 0.59^{a}

Values are the average of triplicate measurements ± standard deviation. AP = addition of pitaya powder; control = (80:20) rice/chickpea. EI = Expansion index, BD = bulk density. Columns with different letters present significant differences ($p < 0.05$).

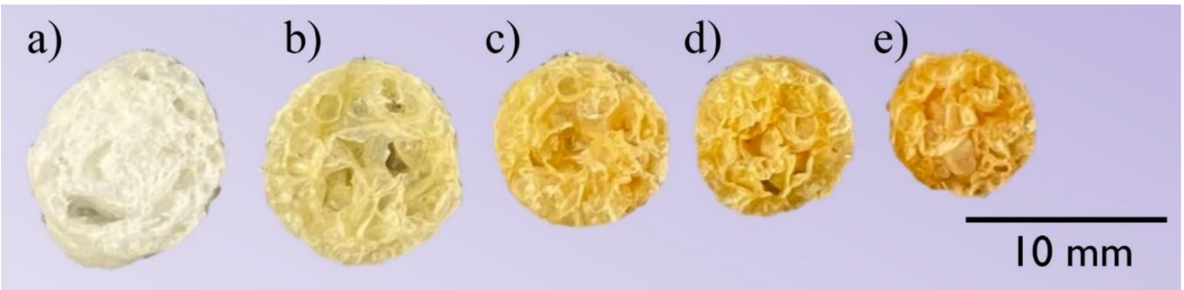

Figure 1. 3G snacks expanded by microwave: a) Control (80:20 rice/chickpea proportion), b) T-2.5, c) T-5.0, d) T-7.5, e) T-10.

The bulk density values were significantly affected ($p < 0.05$) by the pitaya powder concentration. The extruded control presented the highest BD, which was significantly different ($p < 0.05$) compared to treatments with pitaya powder, whereas the 10% pitaya treatment presented the lowest BD (Table 1). BD was positively correlated with EI ($r = 0.81$, $p < 0.01$) after extrusion, which indicates that when the product expands more, it tends to develop a more rigid and consistent structure, which is reflected in an increase in both the EI and hardness, being less dense and more fragile. The addition of pitaya powder reduced the BD; this effect can be attributed to the lower amount of gelatinized starch, which reduces the structural network, limits expansion capacity, and results in more compact pellets [22–25]. After microwave expansion, the BD decreases since the snack expands, reducing the mass per unit volume of the product [13,26]. BD was negatively correlated with EI ($r = -0.94$, $p < 0.01$), which indicates that products with more porous and lighter structures generate less dense products [13, 26]. The addition of 10% pitaya powder resulted in the highest BD value, which was significantly different from that of the other treatments. This behavior was due to the structures being less porous and lighter, which generated more compact products. Similar results were reported by Kantrong et al. [16] and Zambrano et al. [19], who reported that microwave expansion significantly reduced BD and increased expansion.

3.2. Hardness

Hardness is a parameter that measures the force required to fracture a snack and is directly related to its structural integrity and consumer perception of crispness. The hardness of the extruded products was significantly affected ($p < 0.05$) by the addition of pitaya powder. The control sample presented the highest hardness value, whereas the T-10 presented the lowest hardness value (Table 1). This progressive reduction in hardness with increasing pitaya concentration may be attributed to the greater content of soluble sugars, which weaken the starch–protein network during extrusion, interfere with starch gelatinization, and result in less compact and more open structures, thereby reducing mechanical strength [22,23]. The EI was positively correlated with hardness ($r = 0.91$, $p < 0.01$), indicating that samples with greater expansion may exhibit greater fracture resistance. Similar results were reported by Igual et al. [14] for a 3G snack with added beetroot powder. After microwave expansion, the hardness values decreased significantly in all the treatments, with an average reduction of approximately 75% (Table 1). The control and T-2.5 presented the highest values without significant differences ($p > 0.05$), whereas the T-10 had the lowest EI values. The decrease in hardness after expansion is primarily due to the formation of internal pores and a decrease in bulk density resulting from the increase in vapor pressure during microwave heating [12,14]. A negative correlation was found between hardness and BD ($r = –0.88$, $p < 0.01$), indicating that less dense products exhibit greater expansion, crispness, and fragility, which are desirable attributes in third-generation snacks. Similar relationships have been reported by Kantrong et al. [16] and Zambrano et al. [19] in 3G snacks enriched with plant-based powders, where increased porosity and reduced textures are present.

3.3. Chemical properties

3.3.1. Total betalain content (TBC)

The TBC values of the raw mixtures, extruded products, and microwave-expanded snacks are shown in Table 2. The addition of pitaya powder significantly affected ($p < 0.05$) the TB content. After the thermal process, a decrease in the TB content was generated in the samples. The highest TBC value was obtained with the addition of the highest amount of pitaya powder (Table 2), reaching a value of 69.72 mg/g d.b. for T-10. However, a significant reduction was observed after thermal processing, resulting in an average decrease of 33% between treatments with pitaya powder addition. The treatment with the highest TBC after extrusion was T-10, which was significantly different ($p < 0.05$) than the other processed treatments (Table 2). TBC reduction is attributed to high temperatures, which lead to the degradation of betalains through isomerization, bond hydrolysis, decarboxylation reactions, and oxidation, resulting in a gradual change from red to yellow color [14, 27]. Similar results were reported by authors such as Igual et al. [14] and Acurio et al. [12] in corn-based extruded snacks with the addition of beetroot powder, with losses ranging from 30% to 58%. After the microwave expansion process, a new reduction in TB was generated, which was due to heating; increased water mobility enhances the dissolution and subsequent degradation of these pigments [12]. The highest levels of TBC were observed in the T-10 treatment, which were significantly different than the other treatments, resulting in greater orange pigmentation (Figure 1a) and achieving a retention of 30%. TBC was negatively correlated with hardness ($r = -0.89$, $p < 0.01$) and EI ($r = -0.95$, $p < 0.01$), showing that more degradation of bioactive compounds is associated with more compact, less porous structures, which increase hardness and reduce EI. TBC, on the other hand, was positively correlated with AA ($r = 0.95$, $p < 0.01$) and TPC ($r = 0.86$, $p < 0.01$), indicating that the pigments strongly influence the antioxidant effect of the snack in the pitaya powder. These trends among variables indicate that greater product expansion is associated with lower bioactive compound content.

3.3.2. Total phenol content and antioxidant activity

The TPC values of the raw mixtures, extruded products, and microwave-expanded snacks are shown in Table 2. The addition of pitaya powder significantly affected ($p < 0.05$) the TPC. The phenolic compound content in the unprocessed control was 13.97 ± 0.35 mg GAE/100 g d.b. TPC increased up to 3.4 times with the addition of the highest amount of pitaya powder (Table 2). After extrusion, the values of the TPC increased compared with those of the raw material, generating values between 39.06 and 72.78 mg GAE/100 g d.b. (Table 2). The highest TPC values were generated in T-10, increasing by 60%, as determined in the raw mixture. The increase in TPC is due to the chemical transformation of betalains due to the effects of high temperatures and shear stresses during the extrusion process, which results in decarboxylation, hydrolysis, and oxidation, generating degradation products such as betalamic acid, cyclo-DOPA derivatives (5-O-b-D-glucoside), or decarboxylation products [28,29]. These show important antioxidant activity despite the loss of the original color of betalains, since they can capture free radicals and act as antioxidant agents [28–30]. After microwave expansion, a reduction in the TPC is observed due to increased temperature, leading to breaking bonds, decarboxylation, or oxidation of the compounds formed after extrusion [14,31]. Despite this additional thermal process, the bioactive content of the 3G snacks increased, with an average 38% increase in TPC in the formulations with the highest levels of pitaya powder added (Table 2). The AA contents of the unprocessed mixtures and the extruded and microwave-expanded samples are shown in Table 2; these were significantly affected ($p < 0.05$) by the addition of pitaya powder. AA shows a similar trend to that of TPC, increasing after extrusion due to the generation of degradation products with antioxidant activity [28,29]. The AA content was positively correlated with the TPC ($r = 0.88$, $p < 0.01$), indicating that the higher the polyphenol content, the greater the antioxidant activity of the products. The highest values were generated in the T5 treatment, which was significantly different from those in the other treatments, with a 3.1-fold increase after the microwave expansion process. Similar results were reported by Igual et al. [14] in 3G snacks made from corn and beet pigments. Despite the thermal process, the 3G snacks generated with the addition of pitaya powder presented high bioactive values and antioxidant activity, making the product highly attractive not only from a nutritional perspective for consumers but also as a functional food with health-promoting properties.

Table 2. Chemical parameters and colors of the 3G snacks with pitaya powder addition.

	AP (%)	Total betalain content (mg/g d.b.)	Betaxanthin content (mg/g d.b.)	Betacyanin content (mg/g d.b.)	TPC (mg GAE/100 g d.b.)	AA (µmol TE/g d.b.)	L*	a*	b*	Color
Raw mixes	2.5	20.06 ± 0.58^{efg}	6.15 ± 0.21^{ef}	13.91 ± 0.37^{ef}	33.05 ± 1.53^{g}	0.61 ± 0.04^{h}	82.96 ± 0.20^{ef}	5.51 ± 0.05^{d}	17.75 ± 0.08^{h}	
	5.0	31.55 ± 1.36^{c}	10.16 ± 0.44^{c}	21.38 ± 0.88^{c}	37.49 ± 1.23^{f}	0.67 ± 0.04^{gh}	74.91 ± 0.63^{ij}	10.56 ± 0.12^{c}	19.88 ± 0.07^{g}	
	7.5	47.14 ± 1.76^{b}	16.50 ± 0.41^{b}	30.63 ± 1.35^{b}	44.55 ± 0.97^{e}	0.71 ± 0.01^{gh}	73.52 ± 0.26^{j}	14.03 ± 0.13^{b}	19.68 ± 0.06^{g}	
	10	69.72 ± 0.88^{a}	22.20 ± 0.38^{a}	47.51 ± 0.98^{a}	48.28 ± 0.42^{d}	0.78 ± 0.01^{gh}	69.57 ± 0.19^{k}	15.62 ± 0.17^{a}	20.40 ± 0.14^{g}	
	Control	N/D	N/D	N/D	13.20 ± 0.59^{h}	0.81± 0.12^{g}	88.18 ± 0.60^{b}	-0.61 ± 0.03^{j}	12.97 ± 0.13^{f}	
Extrusion process	2.5	18.48 ± 0.24^{gh}	7.47 ± 0.20^{de}	11.01 ± 0.03^{fgh}	39.06 ± 1.60^{f}	0.92 ± 0.04^{g}	83.53 ± 0.58^{d}	-1.72 ± 0.06^{j}	31.79 ± 0.79^{e}	
	5	23.52 ± 0.06^{ef}	8.71 ± 0.25^{cd}	14.81 ± 0.31^{e}	49.13 ± 1.06^{d}	1.82 ± 0.12^{e}	80.55 ± 0.13^{g}	-0.48 ± 0.04^{h}	39.88 ± 0.33^{b}	
	7.5	24.50 ± 0.10^{de}	8.43 ± 1.10^{cd}	16.07 ± 1.21^{de}	69.98 ± 1.35^{ab}	2.88 ± 0.13^{b}	74.47 ± 0.74^{ij}	3.39 ± 0.09^{f}	39.30 ± 0.49^{b}	
	10	32.93 ± 2.31^{c}	9.19 ± 0.73^{cd}	18.73 ± 1.56^{cd}	72.78 ± 0.93^{a}	3.21 ± 0.14^{a}	73.79 ± 0.20^{j}	4.42 ± 0.10^{e}	42.66 ± 0.95^{a}	
	Control	N/D	N/D	N/D	7.43 ± 0.18^{i}	0.53 ± 0.01^{i}	86.51 ± 0.61^{c}	-0.45 ± 0.03^{j}	13.33 ± 0.10^{f}	
Microwave expansion	2.5	12.14 ± 0.61^{i}	4.91 ± 0.34^{f}	7.04 ± 0.27^{i}	27.77 ± 0.87^{h}	0.88 ± 0.06^{g}	85.26 ± 0.57^{d}	-1.42 ± 0.08^{i}	27.79 ± 0.30^{f}	
	5	14.11 ± 1.09^{i}	5.22 ± 0.36^{f}	9.40 ± 0.75^{hi}	37.75 ± 1.30^{f}	1.30 ± 0.03^{f}	81.43 ± 0.14^{fg}	0.59 ± 0.04^{g}	34.71 ± 0.09^{d}	
	7.5	15.65 ± 1.26^{hi}	5.38 ± 0.40^{f}	10.92 ± 0.91^{ghi}	60.83 ± 0.29^{c}	2.16 ± 0.13^{d}	77.17 ± 0.63^{h}	3.38 ± 0.16^{f}	34.06 ± 0.31^{d}	
	10	19.27 ± 0.54^{gh}	6.15 ± 0.18^{ef}	12.59 ± 0.73^{efg}	67.02 ± 1.97^{b}	2.47 ± 0.09^{c}	75.39 ± 0.61^{i}	4.43 ± 0.08^{e}	36.37 ± 0.39^{c}	
	Control	N/D	N/D	N/D	7.74 ± 0.24^{i}	0.55 ± 0.03^{i}	90.69 ± 0.44^{a}	-0.40 ± 0.02^{j}	10.52 ± 0.06^{f}	

Values are the average of triplicate measurements ± standard deviation. AP = addition of pitaya powder; control = (80:20) rice/chickpea proportion. TPC = total polyphenol content; GAE = gallic acid equivalent; AA = antioxidant activity; TE = Trolox equivalent; d.b. = dry basis. Color images were obtained from the EasyRGB color calculator.

3.4. *Color parameters*

The incorporation of pitaya powder significantly affected ($p < 0.05$) the color parameters (L*, a*, and b*) of the third-generation snacks (Table 2). The L* value, which indicates luminosity, decreased progressively with increasing pitaya addition. The control sample presented the highest lightness, whereas the 10% pitaya treatment exhibited the lowest lightness (Table 2), resulting in darker shades because the concentration of pitaya powder (L* = 59.29 ± 0.34) increased. The parameter L* was negatively correlated with TBC ($r = 0.93$, $p < 0.01$), indicating that an increase in the content of compounds results in lower luminosity in the samples. After thermal processing, an increase in luminosity was observed, yielding the highest values in the T-2.5, which was significantly different ($p < 0.05$) from those of the other treatments. This increase in L* can be attributed to browning and pigment degradation due to Maillard and caramelization reactions during extrusion, generating pigmentation changes from pink–red to an orange–yellow color [19,30,31]. A similar behavior has been reported by Zambrano et al. [19] and Kantrong et al. [16], who reported decreased brightness in extruded snacks enriched with natural colorants due to the thermal degradation of bioactive compounds. The a* parameter, associated with red–green tones, increased significantly ($p < 0.05$) with increasing pitaya content, ranging from negative values in the control to the highest value in the T-10 (Table 2), which was significantly different from the results of the other treatments. This increase is due to betacyanin pigments (red–violet) found in the red pitaya capsule (a* = 34.89 ± 0.16), which intensifies the reddish coloration of the snacks [22,31]. The reduction in pigmentation of the a* samples was positively correlated with the TBC ($r = 0.93$, $p < 0.01$), indicating that an increase in the content of bioactive compounds is associated with higher color values. Conversely, the b* parameter increased with pitaya incorporation, from 13.91 in the 2.5% formulation to 20.40 in the 10% formulation, indicating enhanced yellow to orange tones (Table 2) due to the presence of betaxanthins of pitaya powder (b* = 30.33 ± 0.18). After thermal processing by extrusion, a significant increase in the b parameter was observed, resulting in the highest values in the treatment with the highest addition of pitaya powder, reaching a value of 42.66. This increase in the b* parameter is due mainly to the degradation of betalains and Maillard-derived compounds formed during thermal processing, which generate yellow tones [14,24]. The parameter b* was positively correlated with the TBC ($r = 0.99$, $p < 0.01$), indicating that greater pigmentation of the products results in greater collection of active compounds. Similar increases in b* values have been reported in extrudates fortified with powders rich in carotenoids and betalains [22,25].

3.5. X-ray determination

Figure 2 presents the X-ray diffraction (XRD) patterns of the raw materials and extruded samples. The analysis revealed significant structural modifications in the crystalline morphology of the rice–chickpea mixtures after the extrusion process. Raw rice exhibited a characteristic A-type cereal starch pattern (Figure 2a), with prominent diffraction peaks at 2θ values of 15.1°, 17.2°, 18.1°, and 22.8°, corresponding to highly ordered crystalline starch granules. In contrast, raw chickpea flour showed intense peaks at 15.1°, 17.2°, and 22.8°, typical of legume starches exhibiting C-type polymorphic structures (Figure 1b). Similar patterns have been reported by Pozo et al. [32] and Yniestra Marure et al. [33] in studies characterizing native starch granules. After extrusion, the intensity of the characteristic peaks at 15.1° and 17.2° observed in the native materials markedly decreased, indicating partial disruption of the crystalline order due to the combined effects of high temperature, pressure, and mechanical shear during processing [28–30]. Concurrently, new diffraction peaks emerged at 12.8° and 19.8°, showing a similarity between the treatments, possibly due to the similar processing conditions (Figures 2c,f). These generated peaks correspond to the formation of V-type crystalline structures associated with amylose–lipid complex formation [34,35]. These results indicate that extrusion processing generated a transformation of the crystalline structure of rice and chickpea starches, thereby improving the physical characteristics of the resulting products.

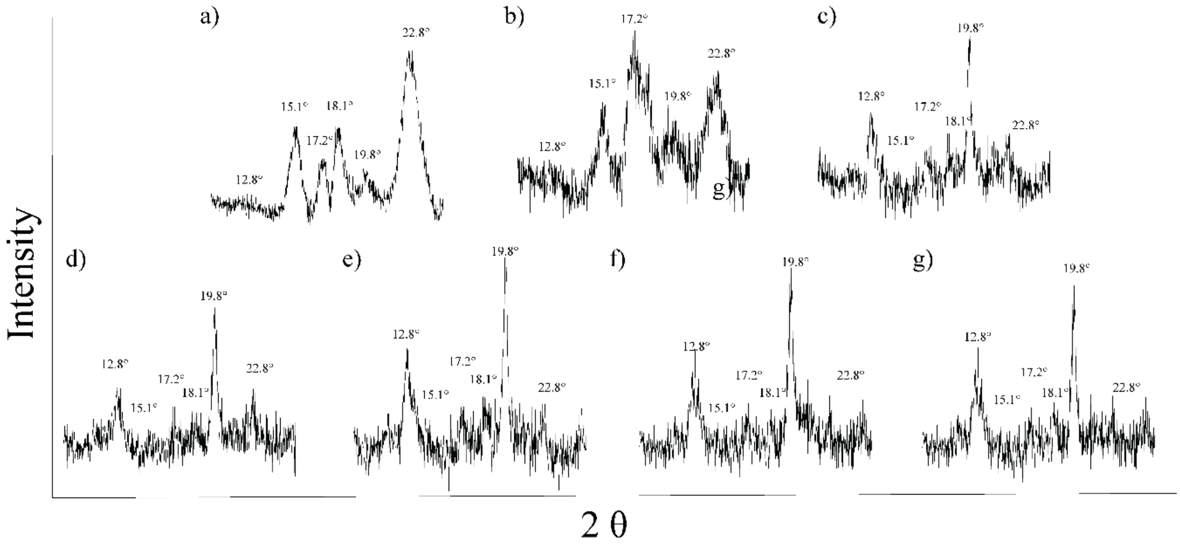

Figure 2. X-ray spectra of samples extruded: a) Raw rice, b) raw chickpea, c) control (80:20 rice/chickpea proportion), d) T-2.5, e) T-5.0, f) T-7.5, g) T-10.

3.6. FT-IR

FT-IR spectra of the raw materials and the rice–chickpea mixtures with added pitaya powder processed by extrusion are shown in Figure 3. The absorption band observed at 1047 cm⁻¹ is attributed to C–O stretching vibrations associated with the ordered or crystalline regions of starch, whereas the band at 1022 cm⁻¹ corresponds to the less organized, amorphous areas. Additionally, the peak near 995 cm⁻¹ is associated with highly amorphous structural arrangements [35]. The 1047/1022 cm⁻¹ intensity ratio is used to estimate the relative degree of molecular organization in the starch matrix [36,37]. On the other hand, the 1022/995 cm⁻¹ ratio reflects the degree of organization within the amorphous regions of starch [34]. The results indicated that extrusion processing modified the molecular ordering of starch. The extrudates presented lower values of 1047/1022 (Table 3) compared to the raw materials, indicating a reduction in crystallinity and a decrease in molecular order in the helical regions of the starch due to gelatinization and thermal disorganization caused by the extrusion process [35–37].

On the other hand, the 1022/995 ratio values remained relatively constant among the treatments, suggesting that the addition of pitaya powder did not significantly modify the organization of the amorphous regions of the starch. However, they showed decreases compared to the unprocessed materials, which indicates a reduction of the orderly arrangement of starch molecules [34,38]. Similar results have been reported by Jia et al. [34] and Wu et al. [38] in extruded products based on semolina and corn starch, respectively. Finally, the band of amide I (1648 cm⁻¹) refers to the stretching vibration of the C=O (carbonyl) group of the peptide bonds, and the signal from amide II (1540 cm⁻¹) is a bending of the N–H group and stretching of the C–N bond. The increase in the 1540 and 1648 cm⁻¹ bands in the formulas compared to raw rice is explained by the proteins contained in the chickpea [39]. Similar results have been reported by Minweyelet et al. [40], where the addition of protein sources to extrudates increased the protein signal detected by FT-IR.

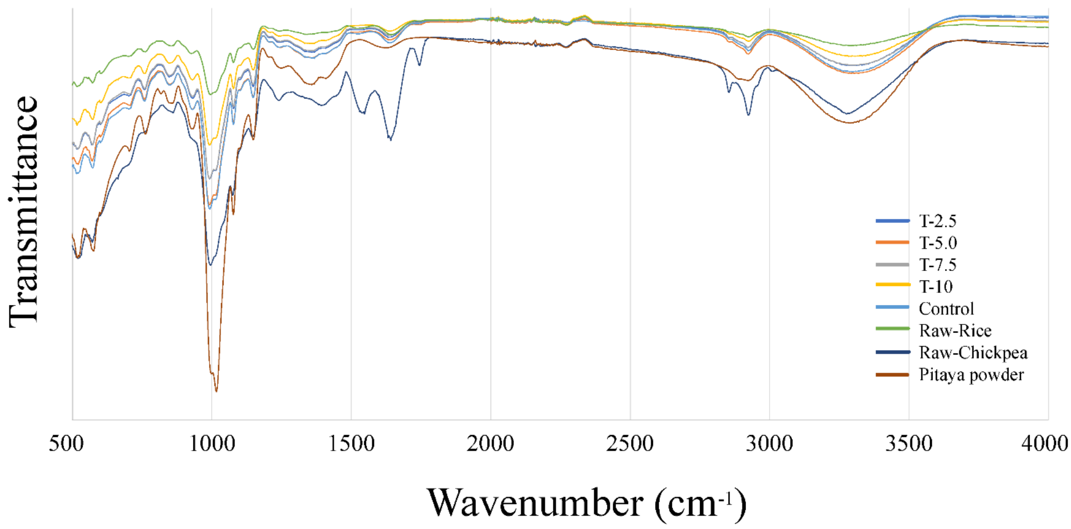

Figure 3. FT-IR spectra: a) raw rice, b) raw chickpea, c) control (80:20 rice/chickpea proportion), d) T-2.5, e) T-5.0, f) T-7.5, g) T-10.

Table 3. Relative crystallinity and intensity of the peaks for the diffraction pattern of the different treatments.

	IR ratios		Area values		Percentage of relative crystallinity at 2 θ					
Treatment	1047/1022	1022/995	1540 cm^{-1}	1648 cm^{-1}	12.8°	15.1°	17.2°	18.1°	19.8°	22.8°
T2.5	0.712	0.907	0.021	0.028	36.6	0.63	5.79	9.26	38.3	8.96
T-5	0.710	0.907	0.022	0.030	32.52	0.9	7.006	10.16	39.73	10.56
T-7.5	0.707	0.904	0.019	0.027	35.31	0.53	5.79	8.36	41.36	8.26
T-10	0.716	0.908	0.020	0.028	36.31	0.79	7.78	8.59	37.26	8.81
Control	0.707	0.906	0.023	0.029	33.16	0.68	7.96	2.12	41.48	15.26
Rice	0.768	0.917	0.017	0.022	ND	22.75	7.07	10.53	5.16	54.48
Chickpea	0.883	0.922	0.102	0.124	ND	16.25	45.21	ND	6.23	32.27

T-2.5 = (2.5% pitaya powder addiction), T-5 = (5.0% pitaya powder addiction), T-7.5 = (7.5% pitaya powder addiction), T-10 = (10% pitaya powder addiction), and control = (80:20) rice/chickpea proportion.

3.7. Scanning electron microscopy

The micrographs of the raw materials, mixtures, pitaya powders, extruded products, and microwave-expanded products are shown in Figure 4. Figure 4a displays the morphology of white rice starch, which consists of small polygonal granules with irregular edges and rough surfaces, averaging approximately 15–20 µm in diameter. This morphology is typical of native cereal starches and is characterized by compound granules with low crystallinity and molecular order [39]. Figure 4b shows chickpea starch granules, which are spherical to oval shaped with smooth surfaces and slightly larger dimensions (18–22 µm). The granules appear partially aggregated and embedded in a continuous protein matrix, indicating the presence of starch–protein interactions that confer greater molecular organization and crystallinity, as previously described by Yniestra Marure et al. [33]. Figure 4c corresponds to the red pitaya powder, which exhibits an amorphous and heterogeneous morphology composed of fine and irregular particles. The structure reveals collapsed agglomerates with porous regions, likely resulting from dehydration and the uneven distribution of pigments and soluble components within the matrix, with an average size of 7.74 µm. In the mixture before extrusion (Figure 4d), the combination of rice, chickpea, and pitaya powders yields a heterogeneous structure where starch granules from both botanical origins coexist within a protein–fiber matrix. The granules still retain part of their native morphology, although partial surface erosion and irregular aggregation are evident, suggesting limited physicochemical interactions prior to thermal processing. The extruded product (Figure 4e) exhibited a completely transformed microstructure, resulting from the intense thermal and mechanical conditions of the extrusion process. The native granular morphology of starch disappears, and an amorphous, compact, and irregular matrix is formed. This indicates starch gelatinization, partial dextrinization, and protein denaturation, as reported by Jia et al. [34] and Wu et al. [38]. The microwave-expanded flour (Figure 4f) exhibited a structure similar to that of the extruded samples after a grinding process of the samples. Figure 4g shows a microwave-expanded pellet with a porous and expanded structure with multiple voids and cavities of different sizes, which are generated by the rapid vaporization of moisture retained by the sample during microwave heating. Finally, an enlargement of the expanded pellet is shown in Figure 4h, where the spaces generated by the process have an approximate size of 155 µm due to the collapse of the air bubbles.

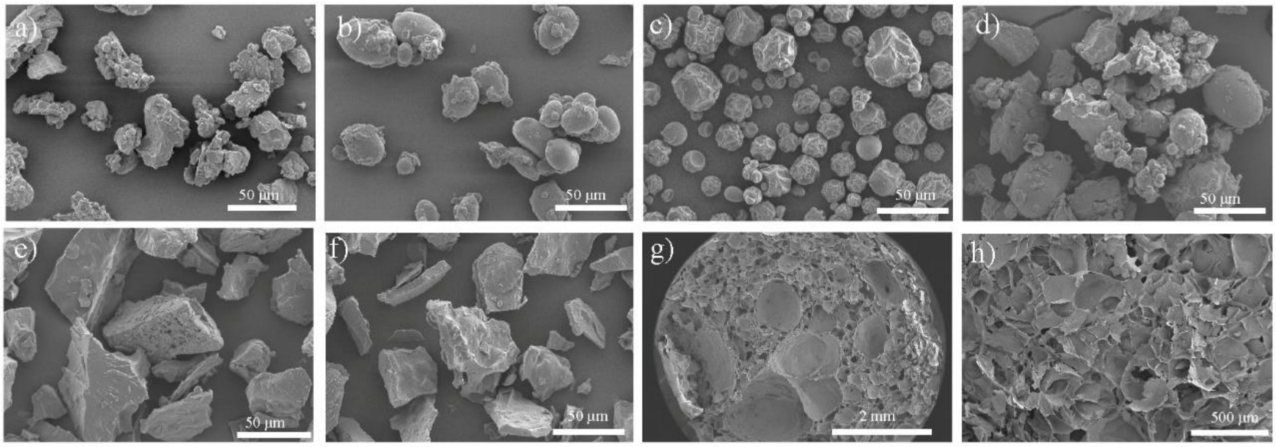

Figure 4. SEM micrographs: a) Raw rice, b) raw chickpea, c) red pitaya powder, d) mixture of rice/chickpea, e) extruded sample with 10% addition of pitaya powder, f) expanded microwave sample with 10% addition of pitaya powder, g) expanded pellet at 20×, h) expanded pellet at 60×.

3.8. Sensory study

The sensory evaluation of third-generation snacks with the addition of red pitaya powder shows that the addition of this ingredient positively influences sensory attributes such as color, hardness, and general acceptability (Table S1). The texture of extruded snacks is one of the main parameters evaluated through sensory testing, as it directly influences consumer acceptance. Attributes such as hardness and crispness mainly determine product quality [41]. The highest value corresponded to treatment T-7.5, which was significantly different ($p < 0.05$) from the lower addition levels. The moderate incorporation of pitaya powder contributes to a firmer and more compact structure, likely due to the interaction of pitaya components with the starch–protein matrix during the extrusion process.

Regarding the characteristics of flavor, crispiness, and aroma, the samples did not show significant differences ($p < 0.05$), which indicates that the addition of pitaya did not adversely affect the sensory perception of these parameters. However, the treatments containing 7.5% and 10% pitaya powder generated the highest flavor values, indicating that the natural color of pitaya flavor affects this sensory parameter. The color perception showed an increase with pitaya powder levels, reaching the highest value at 7.5% addition (Figure 5). This result indicates that pitaya powder enhances the visual appeal of the product, resulting in an orange tone to the snack (Figure S1). On the other hand, treatments T-7.5 and T-10 achieved the highest values of general acceptability, being significantly different ($p < 0.05$) from the control. These results demonstrate that the addition of red pitaya powder enhances the sensory properties and consumer acceptability of rice–chickpea 3G snacks, improving their color and flavor, without compromising texture.

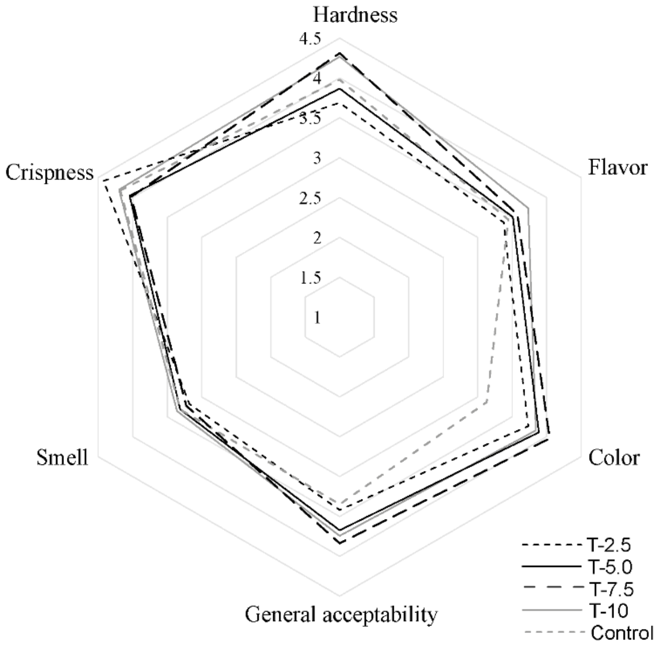

Figure 5. Sensory parameters of 3G snacks with added pitaya powder.

4. Conclusions

The results of this research showed that the combination of extrusion and microwave expansion produced 3G snacks enriched with red pitaya powder at optimal process conditions of 155 °C, 30 rpm, and 24% moisture content. The incorporation of pitaya powder significantly affected the evaluated physicochemical parameters. The optimal incorporation of pitaya powder was 7.5%, which produced a product with improved color and texture, high phytochemical content, achieving a retention of 33% of TBC, an increase of 36% of TPC, and 3 times the AA of the microwave-expanded snacks. Also, the sensory perception of this snack was the highest in terms of hardness and crispness, with a general acceptance of more than 35%. The extrusion process induced structural modifications, reducing the raw material's crystallinity and leading to the formation of type-V complexes. This study provides evidence that incorporating red pitaya powder can improve the nutritional and functional properties of extruded 3G snacks without affecting sensory acceptance. However, this study was performed at a laboratory scale, and industrial-scale extrusion validation should be studied. Additionally, the stability of bioactive compounds during storage and their bioaccessibility were not evaluated, limiting conclusions about the potential health benefits of these snacks.

Use of AI tools declaration

During the preparation of this work was used Chat-GPT and Grammarly in order to correct grammar and style. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Conflict of interest

The authors declare that they have no conflicts of interest.

Author contributions

D.N.-S and A.Q.-R designed the research and collaborated to write the paper; V.R.J-A and R.G.M-G collaborated in the phase Research and write the paper; D.L.-G, L.R.H-O, and E.M.I-A collaborated in the experimental phase research. All authors have read and approved the final version of the manuscript for publication.

References

1. Ambroziewicz ZM, Siemiątkowski R, Łata M, et al. (2024) Long-term health effects of artificially colored foods in adults and children. *J Educ Health Sport* 76: 56522. https://doi.org/10.12775/JEHS.2024.76.56522
2. Sadighara P, Safta M, Limam I, et al. (2023) Association between food additives and allergic reactions in children: A systematic review. *Rev Environ Health* 38: 181–186. https://doi.org/10.1515/reveh-2021-0158
3. Mohidem NA, Hashim N, Shamsudin R, et al. (2022) Rice for food security: Revisiting its production, diversity, rice milling process and nutrient content. *Agriculture* 12: 741. https://doi.org/10.3390/agriculture12060741
4. Saeed SMG, Ali SA, Naz J, et al. (2023) Techno-functional, antioxidants, microstructural, and sensory characteristics of biscuits as affected by fat replacer using roasted and germinated chickpea (*Cicer arietinum* L.). *Int J Food Prop* 26: 2055–2077. https://doi.org/10.1080/10942912.2023.2242602

5. Kumar N, Hong S, Zhu Y, et al. (2025) Comprehensive review of chickpea (*Cicer arietinum*): Nutritional significance, health benefits, techno-functionalities, and food applications. *Compr Rev Food Sci F* 24: e70152. https://doi.org/10.1111/1541-4337.70152
6. Hess JM, Jonnalagadda SS, Slavin JL (2016) What is a snack, why do we snack, and how can we choose better snacks? *Adv Nutr* 7: 466–475. https://doi.org/10.3945/an.115.009571
7. Mattioli R, Francioso A, Mosca L, et al. (2020) Anthocyanins: Chemical properties and health effects. *Molecules* 25: 3809. https://doi.org/10.3390/molecules25173809
8. Khoo HE, Prasad KN, Kong KW, et al. (2011) Carotenoids and their isomers. *Molecules* 16: 1710–1738. https://doi.org/10.3390/molecules16021710
9. Vega EN, Mulero MC, Ruiz VF, et al. (2023) Natural sources of food colorants. *Foods* 12: 4102. https://doi.org/10.3390/foods12224102
10. Montes ED (2025) Preservation of plant-based pigments via spray drying. *Processes* 13: 663. https://doi.org/10.3390/pr13030663
11. Singh S, Aeri V, Sharma V (2023) Encapsulated natural pigments: techniques and applications. *J Food Process Eng* 46: e14311. https://doi.org/10.1111/jfpe.14311
12. Acurio L, Salazar D, Segovia PG, et al. (2023) Third-generation snacks from Andean tubers. *Foods* 12: 2168. https://doi.org/10.3390/foods12112168
13. Qiu C, Hu H, Chen B, et al. (2024) Research progress on the physicochemical properties of starch-based foods by extrusion processing. *Foods* 13: 3677. https://doi.org/10.3390/foods13223677
14. Igual M, Moreau F, Segovia PG, et al. (2023) Valorization of beetroot by-products. *Foods* 12: 176. https://doi.org/10.3390/foods12010176
15. Kojić J, Belović M, Krulj J, et al. (2022) Textural, color and sensory features of spelt wholegrain snack enriched with betaine. *Foods* 11: 475. https://doi.org/10.3390/foods11030475
16. Kantrong H, Klongdee S, Jantapirak S, et al. (2022) Effects of extrusion temperature and puffing technique on physical and functional properties of purpled third-generation snack after heat treatment. *J Food Sci Technol* 59: 2209–2219. https://doi.org/10.1007/s13197-021-05234-x
17. Suárez DN, Pizarro COM, Carrillo EP, et al. (2025) Impact of vegetal protein on microencapsulated pitaya juice. *AppliedChem* 5: 12. https://doi.org/10.3390/appliedchem5020012
18. Neder-Suárez D, Quintero-Ramos A, Meléndez-Pizarro CO, et al. (2021) Evaluation of the physicochemical properties of third-generation snacks made from blue corn, black beans, and sweet chard produced by extrusion. *LWT* 146: 111414. https://doi.org/10.1016/j.lwt.2021.111414
19. Zambrano Y, Mariotti-Celis MS, Bouchon P (2024) 3G extruded snacks enriched with catechin. *LWT* 192: 115674. https://doi.org/10.1016/j.lwt.2023.115674
20. Soto-Dagnino MA, Sánchez-Madrigal MÁ, Heredia-Olea E, et al. (2024) Microencapsulation of pitaya juice (Stenocereus stellatus) by spray drying using mixtures of fructans, whey protein, and modified starch as carrier agents. *Biotecnia* 26. https://doi.org/10.18633/biotecnia.v26.2268
21. Pęksa A, Nemś A, Nadal ES, et al. (2025) Sensory profile and consumer acceptability of third generation snacks from colored flesh potatoes. *LWT* 217: 117460. https://doi.org/10.1016/j.lwt.2025.117460
22. Altaf U, Hussain SZ, Qadri T, et al. (2020) Optimization of extrusion process for development of nutritious snacks using rice and chickpea flour. *J Sci Ind Res* 79: 430–436.
23. Ding QB, Ainsworth P, Plunkett A, et al. (2006) The effect of extrusion conditions on the functional and physical properties of wheat-based expanded snacks. *J Food Eng* 73: 142–148. https://doi.org/10.1016/j.jfoodeng.2005.01.013

24. Lisiecka K, Wójtowicz A, Gancarz M (2021) Characteristics of newly developed extruded products supplemented with plants in a form of microwave-rxpanded snacks. *Materials* 14: 2791. https://doi.org/10.3390/ma14112791
25. Shah FUH, Sharif MK, Butt MS, et al. (2017) Development of protein, dietary fiber, and micronutrient enriched extruded corn snacks. *J Texture Stud* 48: 221–230. https://doi.org/10.1111/jtxs.12231
26. Oyeyinka SA, Akintayo OA, Adebo OA, et al. (2021) A review on the physicochemical properties of starches modified by microwave alone and in combination with other methods. *Int J Biol Macromol* 176: 87–95. https://doi.org/10.1016/j.ijbiomac.2021.02.066
27. Lisiecka K, Wójtowicz A (2021) Effect of fresh beetroot application and processing conditions on some quality features of new type of potato-based snacks. *LWT* 141: 110919. https://doi.org/10.1016/j.lwt.2021.110919
28. Esteves LC, Pinheiro AC, Pioli RM, et al. (2018) Revisiting the mechanism of hydrolysis of betanin. *Photochem Photobiol* 94: 853–864. https://doi.org/10.1111/php.12897
29. Carreón-Hidalgo JP, Franco-Vásquez DC, Gómez-Linton DR, et al. (2022) Betalain plant sources, biosynthesis, extraction, stability enhancement methods, bioactivity, and applications. *Food Res Int* 151: 110821. https://doi.org/10.1016/j.foodres.2021.110821
30. Kayın N, Atalay D, Akçay TT, et al. (2019) Color stability and change in bioactive compounds of red beet juice concentrate stored at different temperatures. *J Food Sci Technol* 56: 5097–5106. https://doi.org/10.1007/s13197-019-03982-5
31. Žilić S, Mogol BA, Akıllıoğlu G, et al. (2014) Effects of extrusion, infrared and microwave processing on Maillard reaction products and phenolic compounds in soybean. *J Sci Food Agr* 94: 45–51. https://doi.org/10.1002/jsfa.6210
32. Pozo C, Rodríguez-Llamazares S, Bouza R, et al. (2018) Study of the structural order of native starch granules using combined FTIR and XRD analysis. *J Polym Res* 25: 266. https://doi.org/10.1007/s10965-018-1651-y
33. Yniestra-Marure LM, Núñez-Santiago MC, Agama-Acevedo E, et al. (2019) Starch characterization of improved Chickpea varieties grown in Mexico. *Starch-Stärke* 71: 1800139. https://doi.org/10.1002/star.201800139
34. Jia B, Devkota L, Sissons M, et al. (2023) Degradation of starch in pasta induced by extrusion below gelatinization temperature. *Food Chem* 426: 136524. https://doi.org/10.1016/j.foodchem.2023.136524
35. Lu H, Ma R, Chang R, et al. (2021) Evaluation of starch retrogradation by infrared spectroscopy. *Food Hydrocolloid* 120: 106975. https://doi.org/10.1016/j.foodhyd.2021.106975
36. Liu X, Zhao X, Ma C, et al. (2024) Effects of extrusion technology on physicochemical properties and microstructure of rice starch added with soy protein isolate and whey protein isolate. *Foods* 13: 764. https://doi.org/10.3390/foods13050764
37. Yao T, Ma M, Sui Z (2023) Structure and function of polysaccharides and oligosaccharides in foods. *Foods* 12: 3872. https://doi.org/10.3390/foods12203872
38. Wu W, Jiao A, Xu E, et al. (2020) Effects of extrusion technology combined with enzymatic hydrolysis on the structural and physicochemical properties of porous corn starch. *Food Bioprocess Tech* 13: 442–451. https://doi.org/10.1007/s11947-020-02404-1
39. Wang LS, Duan YM, Tong LF, et al. (2023) Effect of extrusion parameters on the interaction between rice starch and glutelin in the preparation of reconstituted rice. *Int J Biol Macromol* 225: 277–285. https://doi.org/10.1016/j.ijbiomac.2022.11.009

40. Minweyelet M, Solomon WK, Bultosa G (2021) Teff–rice extruded blends: physicochemical and sensory properties. *Food Res* 5: 173–183. https://doi.org/10.26656/fr.2017.5(2).467
41. Lucas BF, de Morais MG, Santos TD, et al. (2018) Spirulina for snack enrichment: Nutritional, physical and sensory evaluations. *LWT* 90: 270–276. https://doi.org/10.1016/j.lwt.2017.12.032