

Original Research

Effect of rice bran addition on the drying kinetics, energy efficiency and quality characteristics of jujube snacks dried by infrared radiation

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Abstract

The present study aims to evaluate the effects of extrusion and infrared (IR) processing on the nutritional attributes, antioxidant capacity, total phenolic content, and structural properties of snacks enriched with rice bran. A composite blend comprising whole jujube flour (70%), corn starch (10–30%), and rice bran (0–20%) was processed using a single-screw extruder at a screw speed of 50 rpm and a barrel temperature of 30°C. The investigation analyzed the impact of formulation and IR processing conditions—specifically infrared power levels (700, 1000, and 1300 W), radiation distance (5, 10, and 15 cm), and duration (5, 10, and 15 min)—on the drying kinetics and various quality parameters of the jujube-based snacks. Results indicated that the incorporation of rice bran, coupled with the infrared-mediated release of bound phenolic compounds, led to an enhancement in phenolic content and antioxidant activity. Physical analysis demonstrated that increased rice bran concentrations resulted in reduced hardness and crispiness, yielding a softer and less brittle texture. Scanning electron microscopy (SEM) observations revealed that higher rice bran levels progressively disrupted the starch matrix, leading to the formation of smaller cells with thicker walls, which correlated with altered hydration behavior. While moderate rice bran enrichment improved sensory quality, higher inclusion levels diminished overall acceptability. Furthermore, energy analysis indicated that although bran addition lowered mechanical energy demand, infrared heating remained the primary source of energy consumption.

Keywords: Rice bran, Infrared processing, Phenolic compounds, jujube snack

Introduction

Recent research highlights a growing shift in consumer expectations, with individuals increasingly seeking food products that combine appealing sensory attributes with enhanced nutritional quality. This dual demand has become a defining factor in purchasing behavior, prompting food manufacturers to reconsider traditional formulation strategies (Santos *et al.*, 2022). As a result the food industry is compelled to adopt innovative formulation strategies that integrate nutrient-dense ingredients without compromising product acceptability

Extrusion technology has emerged as a versatile platform capable of engineering structural physicochemical, and sensory attributes while maintaining or enhancing the nutritional integrity of raw materials. Recent advances emphasize the importance of optimizing ingredient selection and processing conditions to produce snacks aligned with contemporary dietary expectations (Yadav *et al.*, 2024). Within this context, the valorization of fruit and vegetable-derived byproduct has gained momentum, as these materials offer concentrated sources of dietary fibre and bioactive compounds

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suitable for incorporation into functional food matrices (Pathania and Kaur, 2022). Jujube, a fruit recognized for its rich profile of phenolics, antioxidants, and other bioactive constituents represents a promising candidate for developing health-promoting extruded products. In parallel cereal processing by-products—once regarded as low-value residues—are now increasingly utilized as functional co-ingredients across diverse food systems, including bakery, dairy, meat analogues and infant formulations (Aluthge, 2025; Sharma *et al.*, 2025). Among these, rice bran (RB) stands out, due to its abundance of tocopherols, tocotrienols, polyphenols, γoryzanol and other micronutrients that contribute to its well-documented health benefits (Watchararuij *et al.*, 2008). Beyond its biochemical richness, RB exhibits notable emulsifying and stabilizing properties, enabling the formation of robust protein lipid–water networks even under challenging processing conditions (Tan, 2023). Emerging evidence further suggests that the co-presence of dietary fibre with phenolic compounds may amplify their biological activity, leading to stronger health benefits (Renoldi *et al.*, 2021).

Extrusion remains a key technology for transforming nutrient-rich raw materials and byproducts into cost-effective, structurally tailored snack products. Cold extrusion in particular, offers advantages such as controlled mixing, kneading dispersion, and texturization while minimizing thermal degradation of heat-sensitive compounds (Singh *et al.*, 2014). However, the successful incorporation of high-fibre or phenolic-rich by-products into extruded matrices requires careful control of moisture content, particle characteristics and structural stability (Höglund *et al.*, 2018).

In this regard, modern drying technologies play a crucial role in enhancing the functional performance of recovered materials. Infrared (IR) drying has gained attention as an efficient and energy-saving method capable of delivering rapid uniform heat transfer with minimal quality loss. Studies highlight its potential to improve safety stability, and structural integrity in a wide range of

food applications, positioning IR as a viable alternative to conventional thermal techniques (Zhu *et al.*, 2024; Krishnamurthy *et al.*, 2023).

Specifically, recent studies have demonstrated the effectiveness of continuous infrared technology in optimizing the stabilization of rice bran (Tejaswini *et al.*, 2024). These advantages make IR treated byproducts more suitable for incorporation into processes such as extrusion, where uniform moisture content and improved structural properties are critical for producing high quality, sustainable food products. However despite the growing interest in using fruit and cereal byproducts in extruded snacks, no study has examined the combined incorporation of jujube and rice bran particularly when prepared through infrared drying and their functional behavior during extrusion.

Material and Method

Raw materials and blend preparation

A composite flour blend was formulated using jujube powder, corn starch, and rice bran according to the proportions listed in Table 1. The base jujube powder contained 6.45% protein, 2.9% fat, 3.7% ash, 81.19% total carbohydrates, and 5.76% moisture on a dry-weight basis.

The raw materials were mixed to obtain blends containing 0–20% rice bran and 0–30% corn starch, while maintaining jujube powder at 70% across all formulations. To prepare the dough, the blended flour was hydrated with distilled water to achieve a 25% dry-matter content, ensuring proper consistency for extrusion. The mixture was homogenized using a laboratory mixer (KitchenAid Professional 5 Plus, Troy, Ohio, USA) for 10 minutes, producing a uniform paste. The hydrated blends were then held at room temperature overnight to allow moisture equilibration, a step known to improve dough handling and extrusion stability. The selected formulation ranges were informed by previous findings on functional performance and sensory quality of similar composite systems, as well as methodological considerations reported by Akbari *et al.* (2026).

Table 1. Proportional composition of raw materials in the formulations .

Raw Materials	RB 0%	RB 10%	RB 20%
Jujube powder(%)	70	70	70
Rice bran(%)	0	10	20
Corn starch(%)	30	20	10

Extrusion processing

Cold-dough extrusion was carried out using a Brabender single-screw extruder (Model D47055, Brabender GmbH & Co. KG, Duisburg, Germany). The barrel had an L/D ratio of 26:1 and was equipped with a standard screw of approximately 19–20 mm in diameter. Extrusion was performed at a constant screw speed of 50 rpm, with a feed rate of 25 g/min to maintain uniform barrel filling and minimize fluctuations in pressure (Soja *et al.*, 2024; Altaf *et al.*, 2021). A circular die with a 5-mm opening was used to shape the extrudates. The operational parameters were selected based on previous studies, including Soja *et al.* (2024). Throughout the extrusion process, the temperature in all barrel zones was kept at 30 °C, consistent with cold-extrusion requirements (Yadav *et al.*, 2024). After extrusion, the strands were subjected to infrared (IR) drying at three power levels 700, 1000, and 1300 W for (5,10,15) minutes, until the moisture content reached 8.5–9.5%. Drying was performed using a laboratory IR dryer, following the general procedure described by Renoldi *et al.* (2021). The dried snacks were then sealed in airtight zip-lock bags and stored at 25 °C until further analysis.

Infrared (IR) Drying Process

Infrared drying was applied as a post extrusion-treatment to control moisture reduction, stabilize the product structure, and preserve thermolabile bioactive compounds. The freshly extruded strands were immediately transferred to a laboratory IR drying unit to prevent moisture redistribution and surface condensation. Drying was conducted at —three IR power levels 700, 1000 and 1300 W selected based on prior evidence regarding the influence of IR intensity on heat transfer efficiency and phenolic stability in fibre rich matrices (Renoldi *et al.*, 2021). Each sample was positioned at a fixed emitter distance of 10, 20 and 30 cm as a corresponding to the low, center, and high levels of the experimental design. This distance range allowed systematic evaluation of radiant heat flux and its effect on drying uniformity. Drying times of 5, 10 and 15 min were applied to capture both short and extended exposure thermal regimes. During-processing, the IR source operated in continuous mode to ensure stable energy delivery. Moisture loss was monitored gravimetrically, and drying was terminated once the samples reached a final moisture content of 8.5–9.5% a range considered optimal for achieving crisp texture and preventing

microbial growth in expanded snacks. After drying samples were cooled to room temperature and immediately sealed in airtight polyethylene zip-lock bags to prevent moisture uptake. All dried samples were stored at 25 °C until further physicochemical structural, and functional analyses were performed.

Proximate composition

The proximate composition of the samples was determined after grinding the dried snacks using a laboratory grinder (Caso® Design, Germany). All analyses were performed in triplicate. Protein content was quantified using the Kjeldahl method with a Kjeltac System 1002 distillation unit (Tecator; Hoganas, Sweden) applying a nitrogen-to-protein conversion factor of 6.25. Lipid content was measured through the Soxhlet extraction technique using petroleum ether as the extraction solvent. Moisture and ash contents were determined according to AOAC Official Methods (Association of Official Analytical Chemists, 1970). All proximate values were expressed on a dry-weight basis (g/g DW). Total carbohydrate content was calculated by difference, subtracting the measured protein, fat, and ash fractions from the total dry matter. Dietary fiber fractions including total dietary fiber (TDF), insoluble dietary fibre (IDF) and soluble dietary fibre (SDF) contents were quantified using the AOAC 991.43 enzyme-gravimetric method incorporating minor adjustments based on Ribeiro *et al.* (2023). Fiber results were reported as g/100 g DW, and all measurements were conducted in triplicate to ensure analytical reliability.

Bioactive compounds and bioactivities

For the determination of total phenolic content (TPC) and antioxidant activity, all samples were grounded to obtain a uniform powder, which was subsequently passed through a 115-mesh sieve to ensure consistent particle size. A portion of 10 g from each optimized formulation was then subjected to solvent extraction using 100 mL of a methanol–water mixture (80:20, v/v). The suspensions were maintained at 30 °C under continuous shaking for 8 h to facilitate efficient release of phenolic compounds and antioxidant constituents. Following extraction, the mixtures were centrifuged and the clarified supernatants were collected. The extracts were stored at –4 °C until analysis following the general extraction principles outlined by Akbari *et al.* (2026) and Farhadi & Javanmard (2023), with adjustments

tailored to the characteristics of the jujube–rice bran matrix.

Total phenolic content

The total phenolic content of the samples was determined using the Folin–Ciocalteu colorimetric assay based on the analytical framework reported by

Farhadi *et al.*, 2022 with slight procedural adjustments. Gallic acid was used to construct the calibration curve, and all absorbance readings were obtained in triplicate using a UV–VIS (spectrophotometer Lambda Perkin Elmer. For each measurement 0.5 mL of the extract was combined with 2.5 mL of diluted Folin–Ciocalteu reagent (1:10 v/v). After allowing the mixture to equilibrate for 5 min at room temperature, 2 mL of a 7.5(w/v) sodium carbonate solution was added to initiate color development. The reaction mixtures were then kept in the dark for 30 min, after which absorbance was recorded at 760 nm using methanol as the blank. The phenolic content was calculated from the standard curve and expressed as milligrams of gallic acid equivalents (mg GAE) per gram of

dry matter, providing a quantitative measure of the phenolic constituents present in the samples.

Antioxidant capacity (DPPH assay)

The antioxidant potential of the samples was quantified using a DPPH radical-scavenging assay, following the procedure reported by Farhadi *et al.* (2022) with slight procedural adjustments. A freshly prepared 200 µM DPPH solution was combined with serial dilutions of each extract, and the mixtures were kept in the dark at ambient temperature for 30 min to ensure complete interaction between the radicals and antioxidant compounds. The absorbance of the reacted solutions was subsequently recorded at 517 nm using a UV–VIS spectrophotometer (Lambda 25, Perkin Elmer). The radical-scavenging efficiency was expressed as the IC₅₀, defined as the extract concentration required to decrease the initial DPPH absorbance by 50%. IC₅₀ values were obtained through linear regression analysis performed in Microsoft Excel 2013, consistent with the analytical approach described by Mir *et al.*, 2017.

The percentage of DPPH inhibition was calculated using Equation (1):

$$\text{DPPH scavenging activity} = \frac{(A_{\text{control}} - A_{\text{sample}})}{A_{\text{control}}} \times 100 \quad \text{Eq (1)}$$

Where A_{control} represents the absorbance of the DPPH solution without extract, and A_{sample} corresponds to the absorbance after reaction with the extract. This calculation provided a consistent basis for comparing the antioxidant performance of the formulations.

Scanning Electron Microscopy (SEM)

The surface morphology and internal microstructure of snack samples were characterized using Scanning Electron Microscopy (SEM) (Tescan Mira SEM). Before imaging, each specimen ($n = 3$) was coated with a thin gold–palladium film for 180 s using a sputter coater (Quorum SC7620, UK) to enhance electrical conductivity and prevent charging during observation.

All samples were examined in duplicate following the general procedure described by Liu *et al.*, 2022 and Akbari *et al.*, 2026, with minor adjustments to accommodate the specific characteristics of the jujube–rice bran matrix. These modifications included optimizing coating duration and adjusting magnification ranges to capture both surface features and internal structural details of the printed snacks.

Color analysis

The color characteristics of the samples were assessed using a TES-135 colorimeter (Taiwan). Measurements were reported in the CIE-L*a*b* system, where L* (lightness), a* (red–green coordinate), and b* (yellow–blue coordinate). The magnitude of overall color alteration relative to the untreated extrudate was quantified through the total color difference (ΔE), calculated according to the procedure originally outlined by Pedreschi *et al.* (2007). This parameter provides an integrated measure of visual deviation between processed and raw samples, as expressed in Eq. (2).

$$(2) \quad \Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad \text{Eq}$$

In this color space, L* spans from 0 (black) to 100 (white), while negative and positive values of a* correspond to green and red tones, respectively, and negative and positive b* values indicate blue and yellow tendencies (Farhadi, S., & Javanmard, 2023; Sue *et al.*, 2025).

Sensory evaluation

The post-processed snack samples were evaluated sensorially by a group of 20 semi-trained panelists. The attributes assessed included

appearance, color, texture, taste, and overall acceptability, using a five-point hedonic scale. All evaluations were conducted at room temperature under fluorescent lighting, and panelists were provided with tap water to cleanse their palate between samples. The hedonic scale ranged from 1 to 5, where 1 indicated “not acceptable” and 5 represented “highly acceptable” (Farhadi *et al.*, 2022).

Texture Profile Analysis (TPA)

Mechanical texture properties—including hardness, fracturability, crispiness, and adhesiveness—were quantified using a TAHD Plus texture analyzer (Stable Micro Systems, UK). Hardness was defined as the maximum force recorded on the force–time curve, while crispiness was determined from the number of fracture events generated during compression. Fracturability corresponded to the force at the initial structural rupture, representing the onset of mechanical failure. Adhesiveness, calculated from the negative area during probe withdrawal, reflected the tendency of the sample to adhere to surfaces during mastication. A Warner–Bratzler shear blade fitted with a guillotine-type probe was used, operating at a constant crosshead speed of 1 mm/s. All measurements were performed in five replicates following standardized texture analysis procedures. Recent studies have confirmed the suitability of this approach for characterizing the mechanical behavior of expanded cereal-based snacks and fiber-enriched extrudates (Peressini *et al.*, 2015).

Energy Consumption of the Extrusion-Cooking Process

Total energy consumption was obtained by summing the energy used during extruding and IR processing.

$$(3) \quad E_{\text{total}} = E_{\text{extrude}} + E_{\text{cook}} \quad \text{Eq}$$

The total energy demand of the processing system was determined by integrating the mechanical energy consumed during extrusion with the thermal energy delivered by the infrared (IR) heating stage. Mechanical energy input was quantified as Specific Mechanical Energy (SME), calculated from the ratio of motor power and torque load to the mass flow rate of the feed:

$$(4) \quad \text{SME} = \frac{P \text{ Load}}{m'} \quad \text{Eq}$$

where P is the rated motor power (kW), Load is the percentage of motor torque, and m' is the mass flow rate (kg/s). This approach is widely accepted for characterizing energy consumption in food extrusion

processes (Bouasla *et al.*, 2017). The thermal energy supplied by the IR system was estimated using the standard heat transfer relationship

$$(5) \quad Q = P_{\text{IR}} \times t \quad \text{Eq}$$

where P_{IR} is the effective radiant power of the IR emitters (kW) and t is the exposure time (s). This method follows established models for IR energy quantification in food processing, where radiant power and exposure duration determine the net thermal load delivered to the material (Darvishi *et al.*, 2016). The combined SME and IR energy values provided an integrated measure of the total processing energy, enabling comparison of energy efficiency across treatments and facilitating interpretation of structural and functional changes induced by extrusion–IR processing.

Statistical analysis

Statistical analysis of the experimental data was performed using Response Surface Methodology within a Central Composite Design framework to evaluate the effects of power, time, distance, and formulation on multiple quality attributes. A second-order polynomial model was fitted to the responses, and linear, quadratic, and interaction terms were estimated using replicated center points to ensure adequate precision. Total phenolic content, ascorbic acid, textural parameters, soluble fiber, and total color difference (ΔE) were included as dependent variables in the optimization procedure. Multi-response optimization was conducted using the desirability function, and the combination of factors yielding the highest overall desirability was identified as the optimal processing condition. All statistical computations and numerical optimizations were carried out using Design-Expert software (Version 13), with significance set at $p < 0.05$.

Results and Discussion

Optimization of Processing Parameters

To evaluate the influence of processing variables on the functional and structural properties of the product, a three-level experimental design was constructed using Response Surface Methodology. As summarized in Table 2, three factors—power (700–1300 W), time (5–15 min), distance (10–30 cm) were incorporated into the optimization framework. This design enabled systematic assessment of both linear and interactive effects across low, center, and high levels of each factor. The resulting quadratic model demonstrated strong statistical significance ($p < 0.05$), confirming its suitability for predicting the measured responses.

The optimized conditions derived from the model corresponded to 700 W power, 30 cm distance, 5 min processing time, and 10% RB formulation, under which the samples exhibited improved phenolic content, antioxidant activity, and desirable textural

attributes including hardness, crispiness, and fracturability. These findings highlight the coordinated contribution of processing parameters and formulation composition to the overall quality of the final product.

Table 2 Experimental factors and actual levels used in the optimization design

Factor	Description	Units	Levels (Low – Center – High)
A	Power	W	700 – 1000 – 1300
B	Time	min	5 – 10 – 15
C	Distance	cm	10 – 20 – 30

Chemical analysis of the products

The proximate composition of the extruded snacks including moisture, protein, fat, ash, fibre, and carbohydrate was determined according to AOAC (2016). As presented in Table 3, incorporation of rice bran (RB) induced clear compositional shifts in the final products. Protein and ash contents increased progressively with RB level, whereas carbohydrate content declined, reflecting the dilution of starch by fibre-rich bran constituents.

A marked elevation in total dietary fibre (TDF) was observed in RB10% and RB20% formulations, with RB20% exhibiting the highest TDF (≈ 5.1 g/100 g) and insoluble dietary fibre (IDF) (≈ 3.7 g/100 g) values (Table 3). This increase is consistent with the established composition of rice bran, in which cellulose constitutes the predominant insoluble fraction, accompanied by lignin and hemicellulosic sugars such as xylose, galactose, and arabinose (Hernandez-Santos *et al.*, 2025). The inherently porous and capillary-active architecture of IDF enhances the number of hydrophilic binding sites, thereby improving water retention capacity. Recent investigations have demonstrated that IDF promotes hydration, increases internal surface area, and contributes to greater matrix porosity in cereal-based systems (Igwe, 2025).

The compositional trends observed here align with contemporary findings on fibre-enriched extrudates derived from fruit pomaces, where

increased fibre levels reduce expansion, elevate bulk density, and yield firmer, less aerated structures (Ungureanu-Iuga *et al.*, 2024). Such effects become more pronounced when fibre inclusion exceeds 5–10 g/100 g, owing to the limited swelling capacity and structural rigidity of insoluble fibre fractions (Wang *et al.*, 2019).

Dietary fibre fractions (TDF, IDF, SDF) were quantified using the AOAC 991.43 enzyme-gravimetric method, with minor adjustments following Ribeiro *et al.* (2023). Resistant protein was determined for both soluble and insoluble fractions. Moisture content exhibited a slight increase with higher RB levels (Table 3), which is consistent with the strong water-binding affinity of IDF reported in recent hydration-focused studies (Cheng *et al.*, 2026).

Although thermal treatments such as roasting have been shown to reduce TDF and IDF through partial degradation, no such reductions were evident in the present dataset because fibre measurements were conducted prior to IR roasting, indicating that the observed differences arise from formulation rather than thermal modification. Previous works concluded that fruits and vegetables have higher lignin content than wheat as well (Bunzel and Ralph, 2006). For rice bran, it was expected that cellulose would be the principal IDF, followed by 4 and hemicellulose composed of xylose, galactose and arabinose (Zhang *et al.*, 2024).

Table 3. Proximate composition and dietary fibre fractions of extruded snacks formulated with different RB levels.

Variable	RB 0%	RB 10%	RB 20%
Protein (g/100g)	4.2 ± 0.002^c	7 ± 0.042^b	7.4 ± 0.005^a
Fat (g/100g)	1.1 ± 0.001^b	2.14 ± 0.031^a	$2. \pm 0.008^a$
CH (g/100g)	36.8 ± 0.01^a	35.9 ± 0.02^b	33.7 ± 0.03^c
Ash (g/100g)	4.4 ± 0.007^c	3.4 ± 0.050^b	4.1 ± 0.132^a
TDF (g/100g)	2.90 ± 0.01^c	4.20 ± 0.02^b	5.10 ± 0.02^a
SDF (g/100g)	1.30 ± 0.03^b	1.60 ± 0.04^a	1.45 ± 0.03^{ab}
IDF (g/100g)	1.60 ± 0.02^c	2.60 ± 0.05^b	3.70 ± 0.04^a
Moisture (g/100g)	4.5 ± 0.005^a	4.7 ± 0.003^b	5.73 ± 0.061^c

Antioxidant activity

The antioxidant activity of the snack formulations, evaluated through the DPPH radical-scavenging assay, revealed clear differences associated with rice bran incorporation. As shown in Table 4, the formulations containing 10% and 20% rice bran exhibited significantly stronger antioxidant capacity, with 3.7 ± 1.20 and 3.8 ± 1.10 mg AA/100 mg, respectively. In contrast, the control sample (RB 0%) showed markedly weaker activity ($IC_{50} = 4.15 \pm 0.19$ mg/mL; 0.49 ± 0.05 mg AA/100 mg). The similarity between the 10% and 20% RB treatments suggests that antioxidant enhancement does not increase proportionally with higher bran levels, likely due to matrix-related limitations or partial thermal degradation of bioactive compounds, as previously noted by Andriani et al. (2022). These findings align with Martillanes et al. (2021), who reported that although rice bran is rich in antioxidant phenolics, their recovery is strongly dependent on processing

conditions. The protective role of bran is further supported by the 3D response surface plot (Fig. 1), which demonstrates that ascorbic acid retention is highest under milder processing conditions (lower power and shorter time), and that bran-enriched formulations maintain elevated vitamin C levels across a broader range of thermal intensities. This trend is consistent with the TPC behavior illustrated in Fig. 2, where roasted samples exhibited higher antioxidant capacity due to enhanced release of free phenolics. Moreover, the observations corroborate the findings of Santos et al. (2025), who reported that extrusion exerts neutral or positive effects on antioxidant capacity, whereas roasting significantly enhances it across all formulations. Collectively, these results highlight that moderate bran incorporation, combined with controlled thermal exposure, optimizes antioxidant retention and supports the development of nutritionally stable functional snacks.

Table 4. Ascorbic acid equivalent antioxidant activity of 3 snack formulations

Sample	IC ₅₀ (mg/ml)	mg AA/100mg
AA	0.02±0.01 ^a	-
RB 20%	0.46± 0.11 ^b	3.8± 1.10 ^a
RB 10%	0.50± 0.12 ^b	3.7± 1.2 ^a
RB 0%	4.15±0.19 ^c	0.49 ± 0.05 ^b

Values are expressed as mean ± SD. All extracts exhibited significant antioxidant activity ($p < 0.05$).

RB = rice bran; AA = ascorbic acid. Values followed by different lowercase letters (a, b, c) are significantly different ($p < 0.05$)

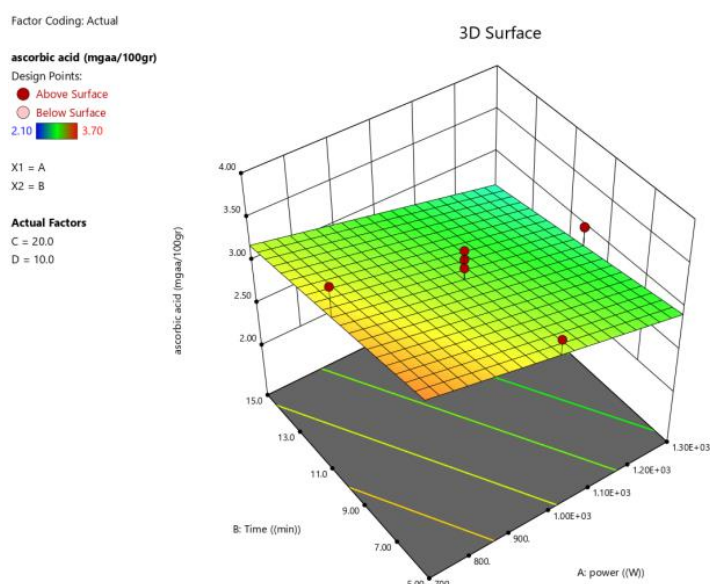


Figure 1. Response surface plot illustrating the effect of microwave power (A) and processing time (B) on antioxidant capacity

Total phenolic content analysis

The evaluation of total phenolic content (TPC) across the snack formulations revealed clear differences associated with the level of rice bran incorporation. As illustrated in Table 5 the RB10% formulation exhibited a significantly higher TPC than both RB0% and RB20% ($p < 0.05$). This pattern indicates that moderate bran enrichment enhances the release and extractability of phenolic compounds more effectively than either the absence of bran or excessive bran addition.

These findings are consistent with the mechanistic explanations reported in recent literature. Santos *et al.* (2025) demonstrated that processing conditions such as cold extrusion can preserve or even increase the bioaccessible phenolic fraction by limiting thermal degradation and promoting the release of ester- and glycoside-linked phenolics from dietary fiber. The increase in free phenolics observed in their study aligns with the enhanced extractability detected in our RB10% sample (Fig 2).

Thermal processing has similarly been shown to disrupt cellular structures and weaken fiber phenolic interactions, thereby improving polyphenol liberation. Pedron *et al.* (2025) reported that roasting softens the nut matrix and facilitates polyphenol release, while Mustafa *et al.* (2021) observed substantial increases in TPC particularly gallic acid and catechin in roasted sweet chestnut. More recently, Liu *et al.* (2025) confirmed that roasting black tartary buckwheat hulls elevates both free and bound phenolic fractions, further supporting the role of matrix disruption in enhancing phenolic availability.

Taken together, the significantly higher TPC in the RB10% formulation supported by both Table 5 and the statistical analysis figure suggests that this level of bran addition optimally promotes the release of bound phenolics from the fiber matrix. This outcome aligns with the mechanistic evidence reported in previous studies, emphasizing that the interaction between processing conditions and raw material structure is a key determinant of the final phenolic profile.

Table 5. Total Phenolic Content of Snack Formulation

sample	Total Phenolic Content (mg GAE/g)
RB 0%	152.896±0.002 ^b
RB 10%	221.138±0.018 ^a
RB 20%	179.821±0.043 ^c

Different lowercase letters (a, b, c) are considered significantly different ($p < 0.05$)

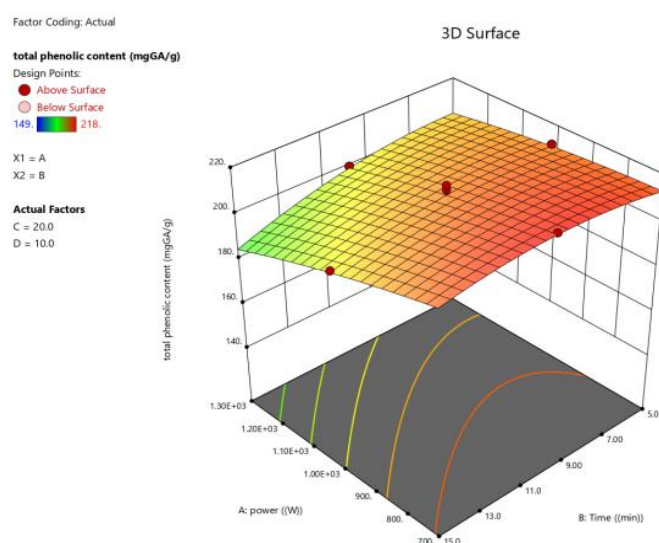


Figure 2. 3D surface plot of TPC as affected by processing time and power at fixed distance and formulation (10%) Texture

The textural properties of the jujube–rice bran snacks were significantly influenced by rice bran level and infrared (IR) drying (Table 6). Although the CCD , design does not include replicated observations statistical differences among treatments were evaluated using Duncan’s multiple range test($p < 0.05$). Superscript letters (a, b, c) indicate statistically distinct groups, and values sharing the same letter are not significantly different. Increasing rice bran from 0% to 20% led to a steady reduction in hardness, crispiness, and fracturability, consistent with the known dilution of the starch matrix by dietary fiber, which limits gelatinization and bubble expansion during extrusion (Yadav *et al.*, 2024; Rashid *et al.*, 2023). Crispiness dropped from 8 to 5 units as RB increased, a trend consistent with the softening of cell walls and the reduced formation of fine, brittle fractures in products with higher internal moisture. Elevated moisture limits the number of micro -fractures generated during biting, thereby diminishing the characteristic crisp sound and sensation. This mechanism aligns with the concurrent decrease in fracturability (131 N to 119

N), indicating that the samples became less brittle and required less force to break.

IR drying further modified these responses by inducing surface dehydration and crust formation, creating moisture gradients that affect fracture behavior. This mechanism aligns with the observed decline in crispiness from 8 to 5 units as rice bran increased, indicating that high fiber levels combined with IR-induced surface hardening limit the formation of a well-defined porous network. The reduction in fracturability in the 20% RB sample is also consistent with reports showing that fiber-enriched extrudates exhibit lower fracture force due to reduced melt elasticity and increased viscosity during extrusion(Yadav *et al.*, 2024). , Meanwhile , adhesiveness remained statistically unchanged suggesting that IR primarily affects structural rigidity and moisture distribution rather than surface stickiness. Overall, the combined effects of rice bran and IR drying produced softer, ,less crispy snacks reflecting the interplay between fiber-induced matrix disruption and IR-driven moisture redistribution.

Table 6. Textural properties of snack formulations containing different levels of rice bran (RB)

sample	Hardness(N)	crispiness	Fracturability (N)	Adhesiveness (N· s)
RB 0%	156 ± 1.76 ^a	8 ± 1.20 ^a	131 ± 0.7 ^a	0.38 ± 0.04 ^a
RB 10%	144 ± 1.83 ^b	6 ± 1.86 ^{ab}	129 ± 1.76 ^a	0.36 ± 0.19 ^a
RB 20%	139 ± 1.40 ^c	5 ± 0.74 ^b	119 ± 0.23 ^b	0.35 ± 0.021 ^a

Results are reported as mean ± standard deviation. Superscript letters (a, b, c) indicate statistically distinct groups determined by Duncan’s multiple range test ($p < 0.05$). Means sharing the same letter are not significantly different.

Color

The color measurements (Table 7) show that infrared (IR) drying combined with increasing rice bran (RB) levels produced clear, dose-dependent shifts in the chromatic attributes of the jujube–rice bran snacks. Higher RB content led to a marked reduction in L^* , confirming stronger darkening due to the greater pigment load and intensified thermal exposure during IR treatment. The pronounced

increases in a^* and the shifts in b^* values in the 10% and 20% RB samples reflect enhanced red–yellow chromaticity, consistent with phenolic pigment concentration and heat-induced browning reactions. These effects were most evident in the 20% RB formulation, which exhibited the highest ΔE , confirming a strong visual deviation driven by both bran pigments and IR-accelerated Maillard pathways.

Table 7. Determination of Color Parameters (L^* , a^* , b^*) and ΔE value under Infrared radiation

sample	L^*	a^*	b^*	ΔE (Color Difference)
• %RB	20.1 ± 0.6 ^{ab}	43.4 ± 0.5 ^b	−50.7 ± 1.0 ^b	36.2 ± 1.3 ^a
10% RB	17.8 ± 0.5 ^a	48.0 ± 0.4 ^a	−45.3 ± 0.9 ^a	42.5 ± 1.2 ^a
20% RB	16.3 ± 0.6 ^b	60.2 ± 0.6 ^c	−68.0 ± 1.3 ^c	49.3 ± 1.4 ^b

All the values are expressed as mean ± SD of the triplicates obtained. The different alphabetical superscripts in the same row represent that each data is significantly different from the other ($p < 0.05$)

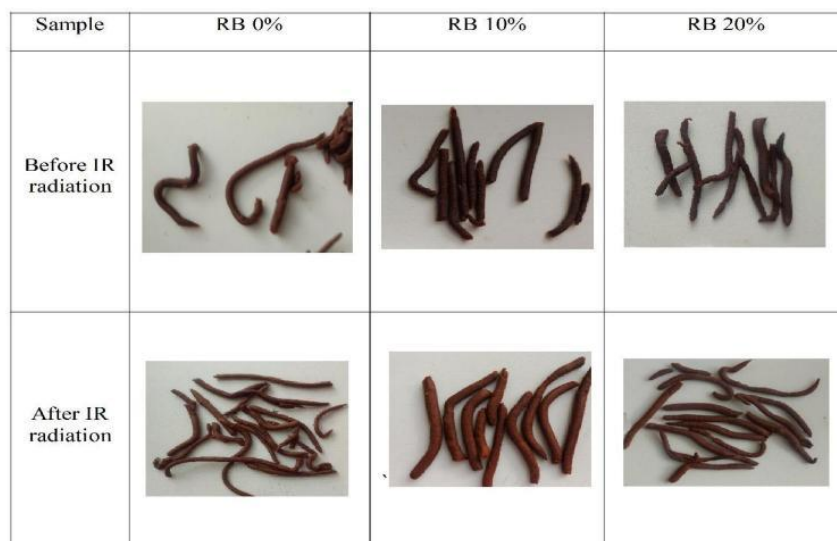


Figure 3. Comparison of snacks produced before and after IR radiation

Water-holding capacity (WHC)

The results presented in Table 6 demonstrate that incorporating rice bran into the snack formulation significantly affects the water-holding capacity (WHC). Overall, the results suggest that the effect of rice bran on WHC in the extruded snacks was not linear, and that the final hydration behaviour was further modulated by IR baking. The reduction in WHC at 10% rice bran may be linked to disruption of the starch matrix, whereas the increase at 20% may reflect the greater contribution of hydrophilic fibre components. The IR process, through its influence on moisture removal and microstructural development, likely played an additional role in defining the ultimate water-holding properties of the products. Similar phenomena have been documented in previous research (Ayoub *et al.*, 2022). The differences observed in water-holding capacity (WHC) among the formulations can also be interpreted based on their microstructural characteristics observed by SEM. In the RB10% formulation, the partial incorporation of rice bran disrupted the continuity of the starch matrix. At this level, the amount of dietary fiber was insufficient to

create an effective network capable of retaining water. The resulting heterogeneous and discontinuous structure likely reduced the number of available water-binding sites, leading to the lowest WHC value (1.51 g/g). The RB0% sample exhibited a higher degree of porosity characterized by large, non-functional macrovoids and smooth starch cell walls, which resulted in moderate water-holding capacity (WHC). In contrast, the RB20% sample showed a more compact microstructure with numerous micro-capillary voids and an interconnected fibrous network, providing more hydrophilic sites for water binding and thereby achieving the highest WHC among the samples. The RB10% sample displayed a disrupted starch structure without the effective formation of a cohesive fibrous network, which explained its relatively lower WHC. These observations are in agreement with the findings of Altan *et al.* (2008), who demonstrated that the inclusion of fiber-rich tomato pomace in extruded snacks leads to the replacement of large, non-functional voids with smaller capillary pores, enhancing water absorption and retention due to both structural and chemical (hydrophilic) effects.

Table 8. Water-holding capacity (WHC) of snacks with varying rice bran levels

Composition (RB/CS/JP)	RB0%	RB10%	RB20%
WHC range (g/g)	1.76 ± 0.03 ^b	1.51 ± 0.05 ^a	1.90 ± 0.07 ^c

Values represent mean ± standard deviation (n=3). RB: rice bran; CS: corn starch; JP: jujube paste. "Different letters indicate significant differences (p < 0.05)

SEM Analysis

The combined assessment of the SEM microstructure and water-holding capacity data indicates that the hydration behavior of the extruded snacks is governed by the structural reorganization caused by rice bran incorporation. In the RB0% formulation, a dense, starch-continuous matrix with smooth granule residues and several large but functionally inactive voids produced a moderate WHC, consistent with starch-dominated systems described by Yang *et al.* (2025). Introducing 10% rice bran interrupted this continuity yet did not supply enough fiber to establish a connected capillary network, resulting in a heterogeneous, weakly hydrated structure with minimal hydrophilic sites—an effect aligned with the matrix-disrupting behavior reported by Li (2025). Similar structural weakening at intermediate fiber levels has been documented by Sinaki and Koksel (2024), who observed reduced expansion and thicker, irregular cell walls in lentil-based extrudates as fiber increased from 10% to 20%.

The seemingly paradoxical combination of high WHC and low final moisture in the RB20% sample is explained by the dual functionality of insoluble dietary fiber (IDF). Recent evidence shows that IDF possesses a porous, sponge-like architecture capable of binding substantial water during dough hydration (Chen *et al.*, 2025; Zhang *et al.*, 2024). However, this same open, fiber-dominated network accelerates

water migration and evaporation during thermal processing, a pattern also noted by Liu *et al.* (2019) and Altan *et al.* (2008). Thus, the elevated WHC of RB20% reflects the hydration capacity of the raw matrix, whereas its reduced final moisture content reflects enhanced water release during heating.

Across all SEM images, increasing rice bran levels produced a greater number of air cells with thicker walls and smaller diameters, although the bubbles lacked the structural strength to expand substantially, consistent with observations by Tovar-Jimenez *et al.* (2015). Surface SEM reveals IR-induced crusting and pore collapse. This phenomenon is closely linked to the spectral selectivity and penetration depth of infrared radiation, which dictates how heat is distributed within the food matrix (Deepika & Sutar, 2024), while cross-section SEM exposes the internal capillary and cell-wall architecture, that governs density, WHC and textural behavior. The resulting texture remained porous yet coarse. Higher fiber levels typically reduce starch availability, limit gelatinization, and diminish expansion. Because IDF absorbs water strongly, it alters gelatinization enthalpy and disrupts bubble stability. Previous studies have shown that moderate fiber additions (up to ~10%) weaken cell-wall integrity and reduce bubble thickness due to excessive water uptake (Nikmaram *et al.*, 2015; Tatari *et al.*, 2020), supporting the structural trends observed in the present work.

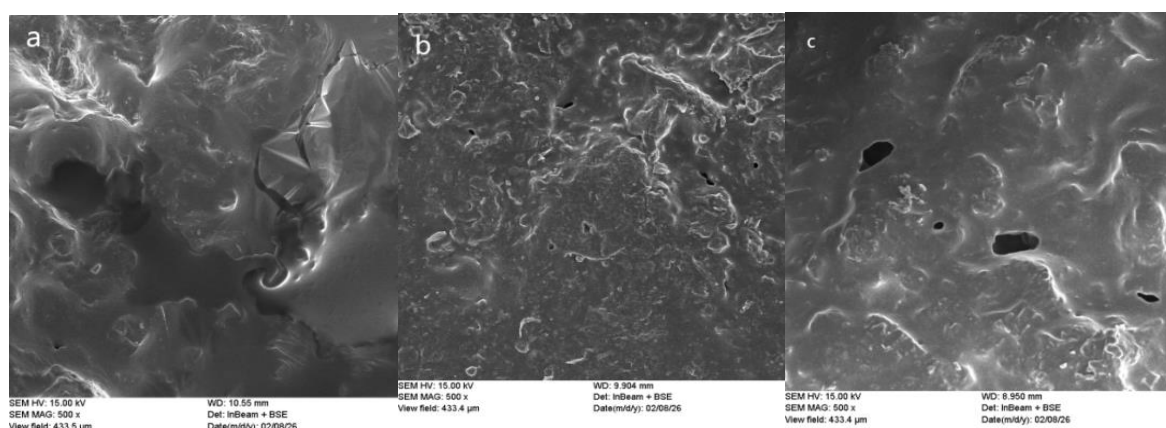


Figure 4. SEM analysis of the surface of 3 snacks formulations RB0% (a) RB10% (b) and RB20%(c) after IR processing

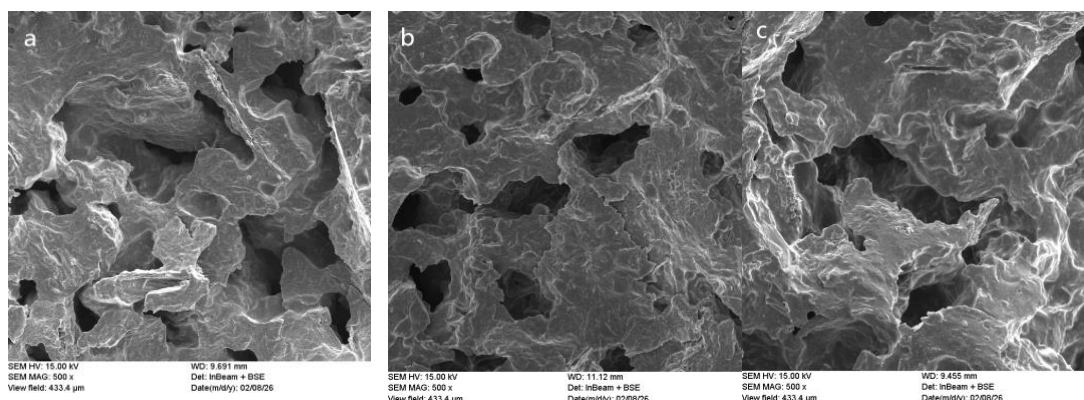


Figure 5. SEM analysis of the cross-sectional snacks RB0% (a) RB10% (b) and RB20%(c) after IR processing

Sensory analysis of extruded snacks

Sensory evaluation (Table 9) showed that rice bran (RB) incorporation noticeably affected the quality attributes of the extruded snacks. The control sample (0% RB) received high scores for color, texture, and mouthfeel, consistent with the typical characteristics of starch-based extrudates. In contrast, the 10% RB formulation achieved the highest overall acceptability (8.2), surpassing both the control and the 20% RB sample. This trend agrees with earlier studies reporting that moderate fiber addition can enhance crispness and flavor retention by allowing sufficient starch expansion during extrusion (Brennan *et al.*, 2013; Foschia *et al.*, 2013). The enhanced performance of the 10% RB sample can be attributed to the balanced interaction between starch and dietary fiber during extrusion and subsequent infrared (IR) heating. Starch gelatinization during extrusion contributes to crispness and structural integrity, while IR heating promotes uniform surface

drying and controlled Maillard browning, improving color and aroma. Similar improvements in surface texture and sensory appeal have been documented for IR-assisted processing of cereal extrudates (pan, 2020; yang *et al.*, 2023).

By comparison, the 20% RB formulation showed a marked decline in sensory performance, particularly in color (5.5) and mouthfeel (6.5). High fiber levels are known to interfere with starch matrix formation, reduce expansion, increase density, and intensify darkening—effects widely reported in high-fiber extruded snacks (Robin *et al.*, 2012). IR heating further amplified surface darkening in this sample, consistent with observations in IR-treated fiber-rich extrudates (Wu *et al.*, 2025).

Overall, moderate fiber enrichment improves sensory quality, whereas excessive fiber disrupts product harmony in IR-finished extruded snacks (Sinaki & Koksel, 2024).

Table.9 Sensory evaluation of extruded snack with different formulation

sample	Colour	Appearance	Texture	Mouthfeel	Overall Acceptability
RB 0%	8.2 ± 0.3 ^a	7.9 ± 0.2 ^b	7.4 ± 0.4 ^a	8.4 ± 0.3 ^a	7.7 ± 0.3 ^b
RB 10%	8.0 ± 0.3 ^a	8.2 ± 0.2 ^a	8.2 ± 0.3 ^b	7.3 ± 0.2 ^a	8.2 ± 0.4 ^a
RB 20%	5.5 ± 0.2 ^b	7 ± 0.3 ^c	7.9 ± 0.3 ^c	6.5 ± 0.2 ^b	7.0 ± 0.3 ^c

Results are reported mean values with their corresponding standard deviations; the averages shown in every column with different letters are significantly different

Extrusion-Cooking Efficiency and Energy Consumption

The results demonstrated that both the mechanical behavior of the material and the overall energy profile of the process were strongly dependent on formulation characteristics, screw speed, and the thermal load applied during the infrared (IR) finishing stage.

At a screw speed of 50 rpm and an L/D ratio of 26, the extruder achieved a mass flow rate of 10.47 ± 0.12 kg/h, corresponding to a specific extrusion energy (SEC) of 0.143 ± 0.006 kWh/kg. Rice bran incorporation significantly affected specific mechanical energy (SME). The RB0% formulation exhibited the highest SME (0.162 ± 0.004 kWh/kg), followed by RB10% (0.151 ± 0.005 kWh/kg) and RB20% (0.139 ± 0.003

kWh/kg). This trend is attributed to the reduction in melt viscosity and frictional heat generation caused by the presence of insoluble fiber, which facilitates material flow through the barrel. Similar observations have been reported for grape pomace (Altan *et al.*, 2009), wheat bran (Brennan *et al.*, 2011), and apple pomace (Zhang *et al.*, 2018), all of which demonstrated decreasing SME with increasing fiber content.

The IR finishing stage contributed a substantial share of the total energy input. At a power setting of 700 W and a processing time of 5 minutes per batch, the IR energy consumption was 0.897 ± 0.031 kWh/kg when normalized to product mass. Based on a batch mass of 0.065 kg. When combined with extrusion energy, the total specific energy requirement for the complete extrusion–IR process reached 1.040 ± 0.037 kWh/kg, this integrated value provides a clearer basis for comparing energy efficiency across formulations and processing conditions.

Conclusion

The findings of this study demonstrated that rice bran incorporation effectively improved the nutritional and functional quality of extruded snacks by increasing protein, dietary fiber, antioxidant potential, and water-holding capacity. Rice bran also modified the microstructure through starch–fiber interactions, leading to changes in texture, color, and hydration behavior, while reducing the mechanical energy required during extrusion. Moderate incorporation (10% RB) achieved the highest sensory acceptability (8.2), whereas higher RB levels promoted a fiber-dominated structure with lower expansion and darker color. The combined extrusion–IR process proved to be an effective approach for producing nutritionally enriched snacks with desirable physicochemical, structural, and sensory characteristics.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest.

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نوع مقاله: پژوهشی

اثر افزودن سبوس برنج بر سینتیک خشک کردن، راندمان انرژی و ویژگی‌های کیفی اسنک‌های عناب خشک شده با تابش مادون قرمز

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چکیده

هدف از این مطالعه، ارزیابی اثرات اکستروژن و فرآوری IR بر محتوای تغذیه‌ای، آنتی اکسیدانی، فنول کل و خواص ساختاری اسنک غنی شده با سبوس برنج است. ترکیبی متشکل از پودر کامل عناب (۷۰٪)، نشاسته ذرت (۱۰-۳۰٪) و سبوس برنج (۰-۲۰٪) در یک اکسترودر تک ماریچ با سرعت ماریچ ۵۰ دور در دقیقه و دمای ۳۰ درجه سانتیگراد اکستروژد شد. تأثیر فرمولاسیون و شرایط فرآوری IR شامل سطوح مختلف توان مادون قرمز (IP) (۷۰۰، ۱۰۰۰ و ۱۳۰۰ وات)، فاصله (۵، ۱۰ و ۱۵ سانتی‌متر) و زمان (۵، ۱۰، ۱۵ دقیقه) بر سینتیک خشک شدن و برخی از پارامترهای کیفی اسنک عناب بود. افزایش فنولیک و آنتی اکسیدانی ناشی از افزودن سبوس برنج همراه با آزادسازی فنولیک‌های متصل به واسطه مادون قرمز بود. سختی و تردی با افزایش سطوح سبوس برنج کاهش یافت که نشان دهنده بافتی نرم‌تر و کمتر شکننده در محصول نهایی است. مشاهدات SEM نشان داد که افزایش سطح سبوس برنج به تدریج ماتریس نشاسته را مختل می‌کند و سلول‌هایی با دیواره‌های کوچک‌تر و ضخیم‌تر تولید می‌کند که با تغییر رفتار هیدراتاسیون مطابقت دارد. غنی سازی متوسط با سبوس برنج کیفیت حسی را بهبود بخشید، در حالی که سطوح بالاتر باعث کاهش مقبولیت شد و تجزیه و تحلیل انرژی نشان داد که با افزودن سبوس، انرژی مکانیکی کمتری وجود دارد، اما مصرف انرژی غالب از طریق گرمایش مادون قرمز است.

کلمات کلیدی: سبوس برنج، فرآوری مادون قرمز، ترکیبات فنلی، اسنک عناب