



Formulations and Optimization of Snacks Enriched with Mango Seed Kernel and Egg Shell Powders to Modulate Satiety for Obesity Management

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Abstract

Overcoming the clinical failure of weight management caused by post-prandial hunger, a scalable and functional food matrix is needed that can modulate the satiety mechanism of the gut-brain axis. Formulation and optimization of a unique snack matrix containing bioactive-dense Mango Seed Kernel Powder (MSKP; 0-8% w/w) and bio-mineralized Eggshell Powder (ESP; 1% w/w) were used to address appetite, glycemic index, and modulation of metabolic lipids. Rheology, microstructure, and chemical analysis revealed that MSKP incorporation increased dietary fiber content up to 6.30%, increased structural calcium content (79.93 mg/100 g) without compromising crude protein content (17.67-18.93%). Microstructure and pasting analysis showed that increased polyphenols fiber content increased bulk density from 0.21 to 0.27 g/cm³ and decreased peak viscosity from 230.4 to 174.3 mPa·s, resulting in a highly cohesive matrix with increased toughness (0.59 kg·s). MSKP inclusion altered carbohydrate digestibility by slowing the hydrolysis of starches: RDS reduced to 64.09% (initial 77.05%), causing a significant increase in SDS (8.98% to 17.99%), RS (up to 22.76%), and lowered e-GI to 31.55. The sensorial profile includes S2-S4 at 2-4% MSKP level that includes scoring for visual appearance (7.3), taste, and crispness. Mixing agricultural waste into a matrix of aerated pulses results in a low-GI, high-fiber, and calcium-enriched functional carrier designed for delaying gastric evacuation and providing prolonged satiety.

1. Introduction

Obesity is a chronic, complex disease, defined by the World Health Organisation (WHO) as an “excess accumulation of fat mass that significantly impairs health” (Aune *et al.*, 2016). Approximately 2 billion adults worldwide live with overweight (a body mass index (BMI) ≥ 25 kg/m²) (Taylor *et al.*, 2013), and over 650 million with obesity (≥ 30 kg/m²).

Worryingly, prevalence has increased 6-fold in just a few decades, up from 105 million in 1975 (Okunogbe *et al.*, 2021; Iqbal *et al.*, 2026). Obesity reduces quality of life and increases the risk of non-communicable disease (NCD), morbidity and all-cause mortality (ACM) (Allison *et al.*, 2023). Globally, obesity costs nearly 2 trillion per year, with direct and indirect costs, including healthcare and economic

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productivity. These figures are expected to rise to 4 trillion by 2035, nearly 3% of global gross domestic product (Tandar *et al.*, 2026; Urooj *et al.*, 2026a). While conventional caloric restriction frequently suffers from poor long-term adherence due to persistent hunger cues, functional dietary strategies focused on satiety modulation offer a promising non-pharmacological alternative (Heeren *et al.*, 2023; Arif *et al.*, 2026a). Functional snacks designed to deliver dense nutritional profiles, delay gastric emptying, and regulate appetite signals can directly replace calorie-dense, low-nutrient convenience food (Vandevijvere *et al.*, 2023; Shabbir *et al.*, 2026). Consequently, formulating satiety-inducing functional snacks represents an actionable paradigm in diet-based obesity management (Popkin & Ng, 2022).

Satiety is a complex physiological state governed by gut brain axis signaling, gastric distension, and metabolic response curves (Monteiro *et al.*, 2026). Postprandial fullness is influenced by the macronutrient composition, dietary fiber structure, and mineral matrix of ingested food (Volek *et al.*, 2024). High-glycemic foods induce rapid blood glucose spikes followed by reactive hypoglycemia, triggering premature hunger (Fazal *et al.*, 2026; Asif *et al.*, 2023). Conversely, matrices rich in insoluble and soluble dietary fibers, complex bioactives, and specific micronutrients suppress appetite by slowing gastrointestinal transit, modulating gut satiety peptide release (such as glucagon-like peptide-1 [GLP-1], peptide YY [PYY], and cholecystokinin [CCK]), and flattening postprandial glucose and insulin curves (Arif *et al.*, 2026b).

Fruit processing by-products represent an underutilized source of dietary fiber and polyphenolic compounds (Vilas-Franquesa *et al.*, 2025; Jones, 2019). Mango (*Mangifera indica* L.) seed kernel an agro-industrial waste accounting for 10% to 25% of total fruit weight (O'Shea *et al.*, 2012) is exceptionally rich in dietary fiber, resistant starches, and essential fatty acids (predominantly oleic and stearic acids) (Forde, & Decker, 2022; Vilas-Franquesa *et al.*, 2024). Mango Seed Kernel Powder (MSKP) contains high concentrations of phenolic acids and flavonoids, including mangiferin, gallic acid, and ellagic acid (Uzombah *et al.*, 2019; Torres-León *et al.*, 2019). The structural interaction between MSKP fiber and bound polyphenols delays carbohydrate hydrolysis, lowers the glycemic index, and promotes sustained satiety via gut microbial fermentation

and delayed gastric emptying (Dicken & Batterham, 2024; Mwaurah *et al.*, 2020).

Each year, approximately million tons of waste is generated from eggshells disposed of in landfills (Sabate *et al.*, 2018). This waste is challenging to manage because of odor and microbiological development (Chen *et al.*, 2025; Chaudhry *et al.*, 2026). However, eggshells have potential applications as a solid byproduct. They can be modified and used in various industries such as metal, polymer, and ceramic composites, in the production of biodiesel, heavy metal absorption from wastewater, and even as a biomaterial to substitute bone tissues (Lee & Kim, 2018; Butt *et al.*, 2026). Furthermore, eggshells can be used as a cheap adsorbent for the treatment of contaminated waterways (Rouhani *et al.*, 2018).

Together with dietary fiber, dietary calcium plays a pivotal metabolic role in adiposity regulation and gastrointestinal lipid binding (Younas *et al.*, 2025). Poultry eggshell waste, an abundant environmental bio-waste, comprises approximately 95% calcium carbonate (CaCO_3) alongside essential trace minerals and bio-functional matrix proteins (Richard *et al.*, 2017). Beyond fulfilling micronutrient fortification needs, high dietary calcium intake suppresses lipogenesis, promotes fecal fat excretion through insoluble calcium-soap formation (saponification) in the gut, and enhances satiety through gut-derived satiety signals (Ni *et al.*, 2020; Pearce *et al.*, 2011). Integrating finely ground Eggshell Powder (ESP) provides a sustainable, highly bioavailable calcium source to fortify snack matrices without increasing caloric density (Miranda *et al.*, 2015).

Despite the individual nutritional and therapeutic potentials of MSKP and ESP, their incorporation into edible matrices presents significant formulation challenges. High substitution levels of fruit by-product fibers and insoluble mineral powders can adversely alter dough rheology, moisture retention, textural attributes, and sensory acceptability. Currently, limited scientific literature addresses the combined incorporation of MSKP and ESP within an optimized snack matrix explicitly designed for satiety modulation and obesity control. Therefore, the objective of this study was to design and evaluate a novel, satiety-inducing functional snack fortified with varying levels of MSKP and ESP. Specifically, this research aimed to quantify the nutritional and mineral profiles, evaluate pasting and textural properties, determine in vitro starch digestibility and estimated glycemic index (eGI), and assess

sensory acceptability of the formulations to optimize a sustainable dietary intervention for obesity management.

2. Materials and Methods

2.1. Selection of raw materials

Fresh mango fruits were procured from Jahangir Tareen area, Punjab, Pakistan, for preparation of pulp extraction. Mung bean (*Vigna radiata*) was obtained from local grain market in Faisalabad, Punjab, Pakistan, and processed into pulse flour. Mango seed kernels (MSK) were collected from local orchards in the Punjab region from ripe mango fruits after pulp removal, while food-grade eggshells (ESP) were obtained from local poultry farms and markets in Faisalabad, Punjab, Pakistan. Egg white was used as a foaming agent. All raw materials were selected in basis of food grade quality standards. Analytical-grade chemicals and reagents were used throughout the study.

2.2. Preparation of raw materials

Mango pulp was prepared by washing, peeling, deseeding, and blending the fruit to obtain smooth consistency. Mung beans were cleaned, dried, milled, and sieved to obtain uniform flour. Mango seeds were separated, shade dried, oven dried at 60°C until constant weight, grounded, and passed through a 100-mesh sieve. Eggshells were washed, heat treated at 100°C for sterilization, ground, and sieved (100-mesh) to fine powder.

2.3. Formulation of snacks

Based on the method of Thakur *et al.* (2024) from the preparation of lentil-based crispy snacks, the Snacks were prepared using a slurry and heat gelling process to develop an air pocket-based crispy texture. Mango pulp was used as primary liquid matrix at 40% (w/w). Mung bean flour (*Vigna radiata*) was mixed with MSKP at 5 predetermined

levels (0, 2, 4, 6, and 8% w/w), while eggshell powder (ESP) was incorporated at 1% (w/w) as a mineral fortificant. For slurry preparation, dry ingredients (mung bean flour, MSKP, and ESP) were thoroughly mixed with mango pulp to form a uniform batter. The mixture was kept hydrating and equilibrate at room temperature for sufficient mixing of components. Salt was added according to the formulation requirements to improve palatability. Egg white was whipped at high speed for approximately 5 min until stiff peaks formed to incorporate air into the system. The whipped egg white was then gently folded into the mango-pulp slurry to minimize foam collapse and maintain aeration. The resulting aerated batter was spread uniformly into a thin sheet approximately 1.5-2.0 mm thick and thermally processed in a hot-air oven at 120-155°C until a crisp, porous structure was obtained. The dried crisps were cooled at room temperature (28 ± 2°C), cut into uniform shapes, and packed in airtight laminated pouches for subsequent analyses.

2.4. Formulation design

Five formulations were prepared to evaluate the effect of increasing MSKP incorporation on the physicochemical, nutritional, structural, and sensory characteristics of the snacks. The formulations consisted of a control without MSKP (S0) and four MSKP-enriched formulations containing 2, 4, 6, and 8% MSKP, coded as S2, S4, S6, and S8, respectively. The mango pulp (40%), eggshell powder (1%), and egg white (17%) levels were kept constant across all formulations, while MSKP progressively replaced mung bean flour. Thus, mung bean flour decreased from 42% in S0 to 34% in S8 to maintain a constant total formulation weight.

2.5. Nutritional composition

Chemical composition of snacks was carried out using standard AOAC (2019) protocols, which were used in recent research of functional and fortified foods. Protein and carbohydrate contents of developed crisps were quantified using Kjeldahl procedure (AOAC 981.10) described by Rizvi *et al.* (2022) and Urooj *et al.* (2026b). The factor 6.25 was considered for estimating crude protein from nitrogen content. Moisture content was measured using the hot air oven technique (AOAC 934.01), crude fat content was estimated using Soxhlet technique (AOAC 948.22), whereas crude fiber content was calculated using the acid-alkaline digestion technique (AOAC 978.10). Ash content was determined using method (AOAC 923.03) by incinerating

Table 1. Formulation composition of MSKP- and ESP-fortified satiety-inducing snacks

Ingredients	Control	MSKP Fortification (%)				
	0	2%	4%	6%	8%	
Mango pulp	40	40	40	40	40	
Pulse flour (mung bean)	42	40	38	36	34	
Mango seed kernel powder (MSKP)	0	2	4	6	8	
Eggshell powder (ESP)	1	1	1	1	1	
Foaming agent (egg white)	17	17	17	17	17	
Sample code	S0	S2	S4	S6	S8	

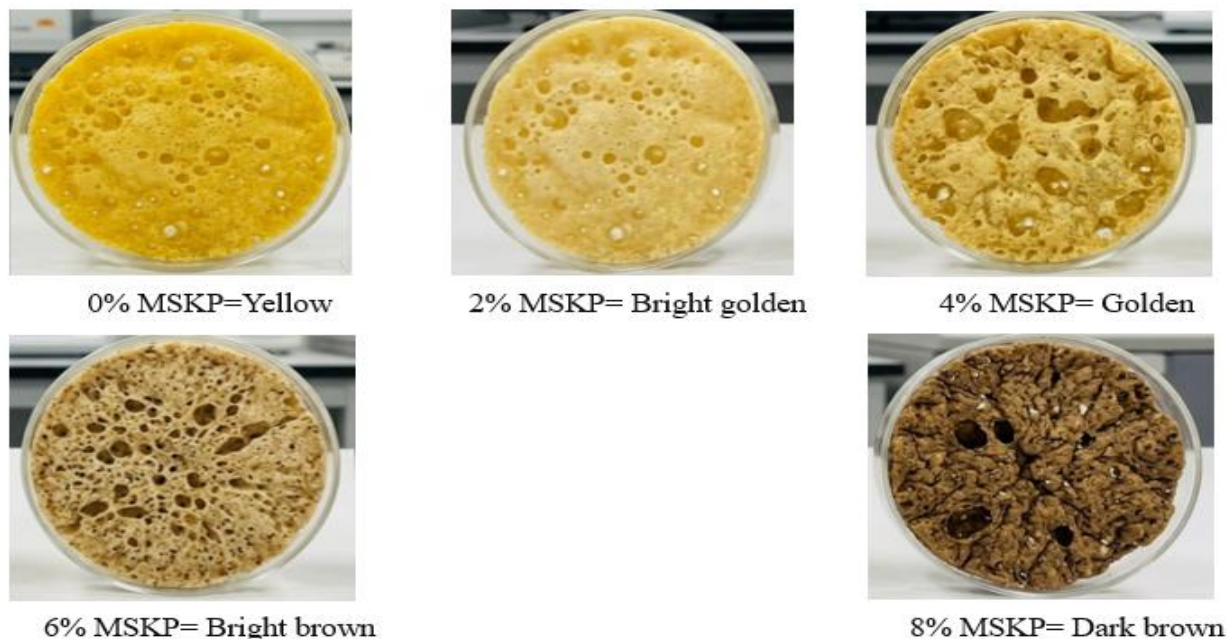


Figure 1. Pictorial representation of formulated snacks

the samples in a muffle furnace at 550 °C until a constant weight was obtained.

2.6. Pasting profile

Pasting properties with varying MSKP levels (0%, 2%, 4%, 6%, and 8%) were carried out by means of a starch pasting cell attached to a rheometer (MCR 52, Anton Paar, Austria) as described by Asif *et al.* (2025a). Pasting properties for snacks containing different concentrations of MSKP (0%, 2%, 4%, 6% and 8%) were carried out by means of a starch pasting cell connected to a rheometer (MCR 52, Anton Paar, Austria). Parameters evaluated during experiments included: Viscosity Properties: Peak Viscosity, Holding Strength, Breakdown Viscosity, Final Viscosity and Setback Values (Peak & Trough), all expressed in millipascal-seconds (mPa·s). Kinetic or Thermal Properties: Peak Time (min) and Pasting Temperature (°C).

2.7. Textural attributes

Textural characteristics of snacked products were determined by using a texture analyzer (TA-XT2, Stable Microsystems, Texture Technologies Corp., Scarsdale, NY) according to Berwig *et al.* (2017), equipped with Texture Expert Version 1.22. A set of 5 samples were compressed to 80% of their average initial diameter using 35 mm compression plate with a test speed of 2 mm/s. Fracturability (N) was assessed. Toughness was determined

by measuring maximum force required for breaking the sample as indicated by Singh *et al.* (2015). Crispiness was also determined based on the peak counts obtained when compressing the sample according to Dogan *et al.* (2007). The internal structure of extruded snacks was examined using scanning electron microscopy (Leica Stereoscan 440, Leica Cambridge Ltd., England).

2.8. Physical characterization

Expansion ratio, piece density, and bulk density of snacks were analyzed using methods of Asif *et al.* (2025b). Expansion ratio (ER) was calculated by dividing the cross-sectional thickness of the extrudate by that of the die orifice (Dev and Gupta, 2024). An average diameter of 15 samples was used to determine expansion for each set of samples. Piece density (g/cm³) was measured using the sand displacement method as outlined by Bows and Dimitrakis (2016), while bulk density was determined from weight or volume ratio (Bisharat *et al.*, 2013). The procedure was repeated 5 times on each sample set. Color analysis was performed with Konica Minolta's Chroma Meter (Model CR-400, Minolta Co. Ltd., Osaka, Japan).

2.9. In vitro hydrolysis index and estimated glycemic index (eGI)

The *in vitro* starch digestion profile and predicted glycemic response of MSKP-fortified snacks were determined

following the multi-enzyme digestion procedure described by Krishnan *et al.* (2021) with minor modifications. 1 g of comminuted snack sample was homogenized in 2 mL of distilled water and made up to 10 mL. The mixture was incubated with 4.0 mL of alpha amylase solution (250 U/mL) for 5 min at 37 °C with steady agitation (200 rpm). The mixture was then acidified to pH 2.0 ± 0.2 using 2 N HCl, treated with 3.0 mL of pepsin solution (1 mg/mL), and incubated for 30 min at 37 °C. Subsequently, the pH was adjusted to 6.0 using 2 N NaOH, followed by the addition of 2.0 mL of pancreatin (2 mg/mL) and 2.0 mL of amyloglucosidase (28 U/mL). The mixture was incubated for 240 min at 37 °C. Aliquots (1.0 mL) were collected at 30-min intervals (0, 30, 60, 90, 120, 150, 180, 210, and 240 min), and the enzymatic reaction was immediately terminated by heating the aliquots in a boiling water bath at 100 °C for 5 min. Glucose concentration in the supernatant was determined using the 3,5-dinitrosalicylic acid (DNS) colorimetric method. Rapidly digestible starch (RDS) was defined as the glucose released during the first 30 min of digestion, whereas slowly digestible starch (SDS) was defined as the glucose released between 30 and 240 min. The in-vitro hydrolysis index (HI) was calculated by expressing the area under the starch hydrolysis curve (AUC) of each MSKP-fortified snack relative to that of white bread, which was used as the reference standard and subjected to identical enzymatic digestion conditions:

$$HI = \frac{(\text{AUC}_{\text{sample}})}{(\text{AUC}_{\text{white bread}})} \times 100$$

The *in vitro* estimated glycemic index (eGI) was calculated using the non-linear predictive equation proposed by Krishnan *et al.* (2021):

$$eGI = 39.71 + (0.549 \times HI)$$

2.10. Acidity profile

2.10.1. Determination of pH value

To measure pH value, 10 g of grounded samples were mixed in 90 mL distilled water in a beaker and homogenized using a homogenizer (T10 basic, IKA, Staufen, Germany), as explained by Cui *et al.* (2024). The suspension was left to stand for 30 min. The pH value was determined using a pH meter (S220, METTLER TOLEDO, Greifensee, Switzerland).

2.10.2. Determination of total titratable acidity (TTA)

Total titratable acidity was determined by taking 10 g of ground snacks samples in 90 mL of distilled water in a beaker, followed by homogenization using a homogenizer

(T10 basic, IKA, Staufen, Germany), as suggested by Cui *et al.* (2024). Each sample was then mixed with 0.5 mL of 1.0% phenolphthalein indicator and titrated with 0.1 M NaOH. The endpoint was determined when a pink color persisted for 30 s. The titratable acidity was calculated using the following equation:

$$TTA (\%) = \frac{c \times (V_3 - V_2) \times K}{m} \times \frac{V_0}{V_1} \times 100\%$$

Where,

c = Concentration of standard NaOH solution (mol/L)

V₃ = Volume of NaOH consumed by sample (mL)

V₂ = Volume of NaOH consumed in blank titration (mL)

m = Sample mass (g)

V₀ = Total volume of diluted sample (mL)

V₁ = Volume of sample aliquot taken for titration (mL)

K = Conversion factor for the predominant acid (0.090 for lactic acid)

2.11. Mineral content

Analysis of minerals such as iron (Fe) and zinc (Zn) was carried out independently based on the procedures recommended by the AOAC International Official Methods of Analysis (2023). Calcium content was estimated to be determined through flame photometer (Maldonado *et al.*, 2020; Chandra *et al.*, 2020). Concentrations of minerals were expressed in mg/100 g dry weight. All measurements were performed in triplicates with blank controls to ensure accuracy, and recovery rates were maintained within 95–105% of actual concentration levels.

2.12. Color characteristics

Color characteristics of snacks samples (S0–S8) were determined using a colorimeter (CR-400, Minolta Co., Osaka, Japan) calibrated using a standard white plate (L* = 97.06, a* = 0.04, b* = 2.01) according to the method used by Cui *et al.* (2024) and Urooj & Asif (2026c) in analyzing color properties of potato crisps. The apparatus measured the CIE color parameters of the crisp samples, such as L* (lightness), a* (red-green coordinate), and b* (blue-yellow coordinate).

Under the system of the apparatus, color measurements of the 5 samples were done thrice, and the average values were obtained. L* denotes lightness on a range from 0 to 100, with zero denoting absolute blackness while 100 indicates total whiteness. The a* parameter represents red-green coordinate, where negative values denote greenness while positive values indicate redness. Lastly, the b* parameter denotes blue-yellow coordinate, whereby negative values

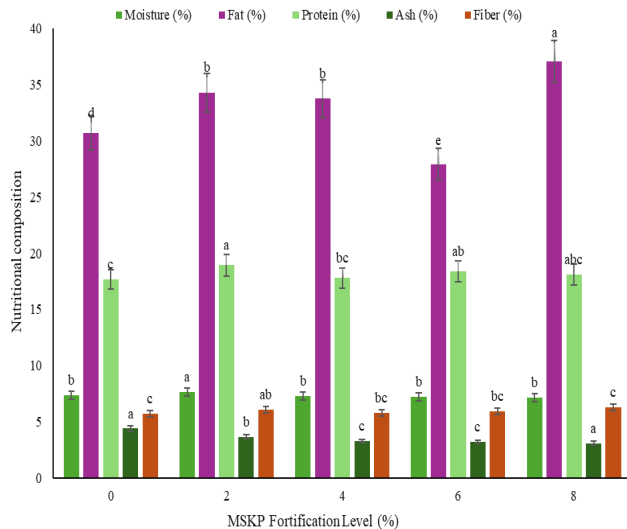


Figure 2. Effect of MSKP fortification on the proximate nutritional composition of snacks

represent blueness, while positive values represent yellowness.

For uniformity, samples were grinded to form homogenous powders passing through a 40-mesh sieve. The samples were poured into Petri dishes and lightly pressed to have a flat surface. The color properties of the sample formulations were measured in triplicates, and L^* , a^* , and b^* . The total color difference (ΔE) between control (S_0) and enriched samples was calculated using the following equation:

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2}$$

where L_0^* , a_0^* , and b_0^* represent the color values of the control sample (S_0), and L^* , a^* , and b^* represent the corresponding values of MSK fortified samples.

2.13. Sensory evaluation

Sensory evaluation of developed snacks was done based on sensory acceptance of biofortified foods and food products method of hedonic sensory evaluation by Urooj *et al.* (2026d) and method of crisps from red guava by Yadav *et al.* (2024). 10 panelists were routine snack consumers consisting of 6 females and 4 males whose ages ranged from 24 to 27 years. and were explained the significance of the trial and sensory descriptors beforehand. The snacks were evaluated for sensory attributes including appearance, mouthfeel, taste, crunchiness, and overall acceptability on a 9-point hedonic scale where “dislike extremely” 1 to “like extremely” 9.

2.14. Statistical analysis

All analytical determinations were performed in triplicate in triplicate ($n=3$), and results were presented as mean and standard errors as described by Huey *et al.* (2024). The effect of MSKP fortification levels on quality and functional attributes of snacks was evaluated using one-way Analysis of Variance (ANOVA) via Statistix 8.1 software (Statistix, Tallahassee, FL, USA). Means were compared using Tukey’s Honestly Significant Difference (HSD) post-hoc test, with statistical significance ($p < 0.05$). Statistically significant differences ($p < 0.05$) among treatment formulations are denoted by error bars.

3. Results & Discussion

3.1. Nutritional composition

MSKP fortification significantly influenced the proximate composition of snacks as presented in Figure 2, showing the distinct nutritional profile of mango seed kernel compared with mung bean flour. Protein content remained relatively stable (17.67-18.93%), indicating that partial substitution with MSKP maintained the high protein value of the product. Fat content showed greater variation, increasing overall from 30.69% in the control to 37.04% at 8% MSKP, which can be attributed to the residual lipids naturally present in MSKP. Moisture content remained consistent (7.18-7.66%), suggesting that MSKP had minimal impact on product dehydration and that all formulations retained moisture levels favorable for crispness and shelf stability. Ash content decreased progressively from 4.41% to 3.12% with increasing MSKP, indicating a slight reduction in total mineral content following substitution. Conversely, dietary fiber increased from 5.71% in control to 6.30% at 8% MSKP, showing the fiber-rich nature of MSKP and its potential to enhance the functional value of the product. MSKP fortification improved the nutritional quality of snacks by increasing dietary fiber while maintaining protein content and acceptable moisture levels. Although ash content declined slightly and fat content increased with higher substitution, the fortified formulations showed an enhanced nutritional profile, supporting the use of MSKP as a sustainable functional ingredient for value added snack development at outlined by Das *et al.* (2019).

3.2. Physical properties

MSKP fortification significantly affected the physical properties of snacks as shown in Figure 3, particularly piece density, bulk density, and expansion ratio. These changes shown the influence of MSKP dietary fiber on matrix formation and expansion during aeration and drying. Piece

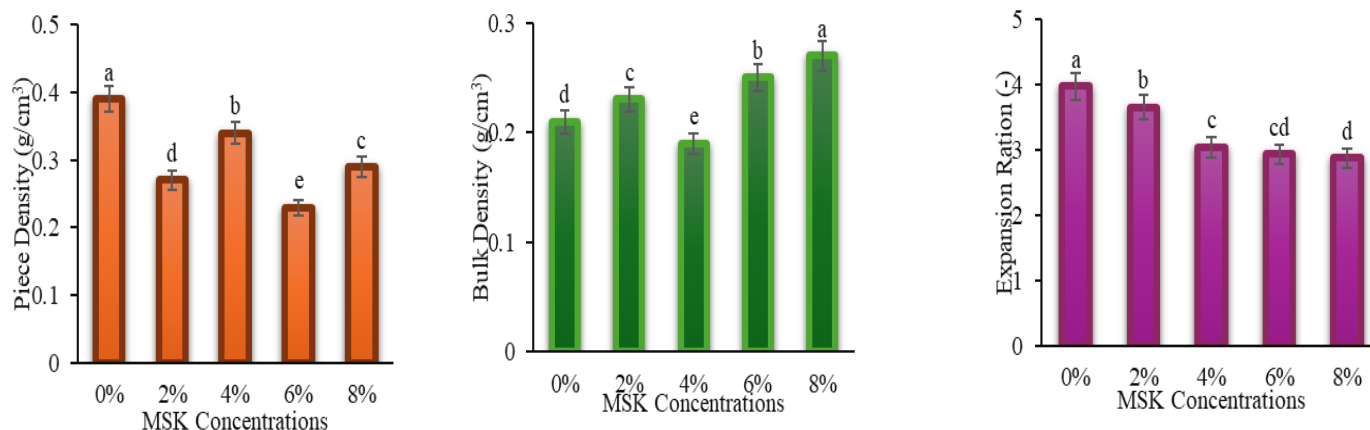


Figure 3. Effect of MSKP fortification on the physical properties (piece density, bulk density, and expansion ratio) of snacks

density ranged from 0.23 to 0.39 g/cm³ and showed moderate fluctuations with MSKP incorporation, suggesting that MSK altered air-cell formation and pore architecture through changes in batter viscosity and bubble stability. In contrast, bulk density generally increased from 0.21 to 0.27 g/cm³ with increasing MSKP, indicating the formation of a more compact and less porous structure. The higher fiber content of MSKP likely increased water-binding capacity and reduced starch availability for expansion, limiting air-cell growth and stability. Consistently, the expansion ratio declined from 3.97 in the control to 2.87 at 8% MSKP, demonstrating that progressive substitution reduced expansion capacity. The dilution of starch by fiber-rich MSKP weakened the starch-protein matrix and restricted air retention during drying, resulting in denser products. The inverse relationship between expansion ratio and bulk density further confirms that reduced expansion produced more compact snacks. MSKP incorporation enhanced the nutritional value of snacks but progressively reduced expansion while increasing bulk density. These findings suggest that moderate MSKP fortification offers a balance between improved functionality and desirable physical characteristics, whereas higher substitution levels may adversely affect product structure and crispness as stated by Yadav *et al.* (2024).

3.3. Pasting properties

MSKP fortification significantly altered the pasting behavior of snack formulations in Table 2, indicating changes in starch gelatinization, paste stability, and

retrogradation. These effects are primarily attributed to the high dietary fiber, lipid, and polyphenol contents of MSKP, which limit starch hydration and modify starch matrix interactions. Peak viscosity generally decreased with increasing MSKP incorporation, from 230.4 mPa·s in the control to 174.3 mPa·s at 8% MSK, although a slight recovery was observed at 6%. This reduction suggests restricted starch swelling due to competition for water and starch-lipid or polyphenol interactions. Meanwhile, peak time (8.38-8.53 min) and pasting temperature (60.96-74.29°C) showed only minor variations, indicating that MSKP had limited influence on the gelatinization process. Holding strength also declined with MSKP fortification, showing reduced paste stability during heating. Breakdown viscosity varied among formulations, with the lowest value at 4% MSKP, suggesting greater thermal stability at moderate substitution levels, whereas higher MSKP increased susceptibility to structural breakdown. Final viscosity and setback exhibited formulation-dependent responses. Moderate MSKP incorporation increased final viscosity, whereas higher substitution reduced setback values, indicating lower starch retrogradation. This behavior is likely due to dietary fiber and polyphenols interfering with amylose reassociation during cooling. MSKP modified starch functionality by reducing peak viscosity and paste stability while limiting retrogradation at higher incorporation levels. These changes are expected to influence processing performance, texture, and storage stability of the developed snacks (Thakur *et al.*, 2024).

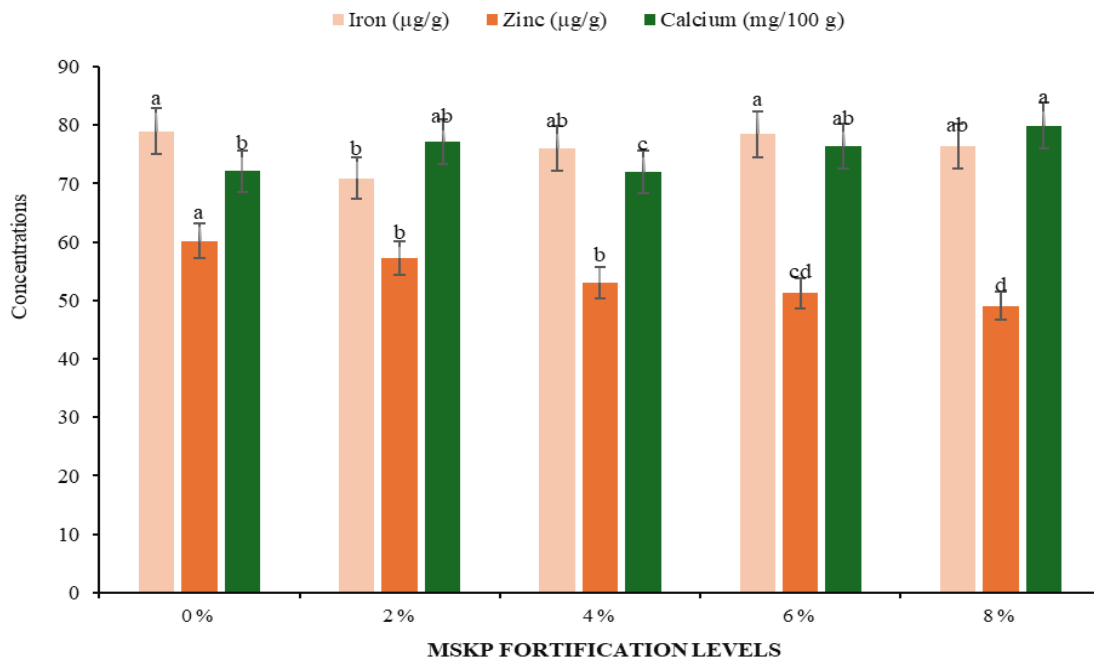
Table 2. Effect of mango seed kernel powder (MSKP) fortification on pasting properties of snack formulations

MSKP level (%)	Peak viscosity (mPa·s)	Peak time (min)	Pasting temperature (°C)	Holding strength (mPa·s)	Breakdown (mPa·s)	Final viscosity (mPa·s)	Setback (peak) (mPa·s)	Setback (trough) (mPa·s)
0	230.40 ± 2.10 ^a	8.53 ± 0.05 ^a	70.64 ± 0.42 ^b	201.40 ± 2.35 ^a	28.97 ± 0.62 ^c	490.20 ± 4.15 ^c	259.80 ± 3.20 ^b	288.70 ± 3.45 ^b
2	224.20 ± 2.45 ^a	8.53 ± 0.04 ^a	60.96 ± 0.38 ^d	197.80 ± 2.10 ^a	26.41 ± 0.55 ^c	534.40 ± 5.20 ^a	310.10 ± 4.10 ^a	336.50 ± 4.25 ^a
4	156.80 ± 1.85 ^c	8.53 ± 0.06 ^a	64.29 ± 0.45 ^c	142.30 ± 1.95 ^c	14.16 ± 0.40 ^d	320.00 ± 3.65 ^c	163.20 ± 2.30 ^d	177.70 ± 2.55 ^d
6	184.70 ± 2.05 ^b	8.40 ± 0.05 ^b	74.29 ± 0.50 ^a	154.00 ± 2.20 ^b	30.68 ± 0.70 ^b	416.20 ± 4.00 ^d	231.60 ± 3.15 ^c	262.20 ± 3.40 ^c
8	174.30 ± 1.90 ^b	8.38 ± 0.04 ^b	70.28 ± 0.41 ^b	132.20 ± 1.75 ^d	34.25 ± 0.68 ^a	510.10 ± 4.85 ^b	149.40 ± 2.10 ^c	230.30 ± 2.95 ^c

3.4. Mineral composition

MSKP incorporation significantly influenced the mineral composition of snacks as depicted in Figure 4, particularly iron, zinc, and calcium. Iron content remained relatively stable (70.89-78.98 µg/g) despite minor fluctuations, suggesting that partial substitution with MSKP had little effect on iron retention during processing. Zinc content decreased progressively with increasing MSKP incorporation, from 60.19 µg/g in control to 49.07 µg/g at 8% MSKP, indicating that mung bean flour contributed more zinc than MSKP. Similar reductions have been

reported in composite flour products where legume flours are replaced with fruit seed-derived ingredients Kaur *et al.* (2022). Calcium content generally increased with MSKP fortification, rising from 72.11 mg/100 g in control to a maximum of 79.93 mg/100 g at 8% MSKP, representing an approximately 11% increase. This enhancement is likely attributable to the intrinsic calcium content of MSKP together with the constant inclusion of ESP across all formulations. MSKP fortification improved the mineral profile by enhancing calcium while maintaining relatively stable iron levels, although zinc decreased with increasing

**Figure 4.** Effect of MSKP fortification on the mineral composition (iron, zinc, and calcium) of snacks

substitution. These findings highlight the potential of MSKP as a functional ingredient for developing mineral-enriched aero-veg crisps without compromising their overall nutritional quality.

3.5. Acidity profile

MSKP incorporation slightly affected the acidity profile of snacks in Table 3, resulting in minor changes in pH and total titratable acidity (TTA). The pH ranged from 5.69 to 5.95, with a slight increase at 2-4% MSKP followed by a decline at 6% and recovery at 8%, indicating that MSKP had a limited effect on the acid-base balance of the product. These variations may show the buffering capacity of MSKP proteins and minerals, together with the contribution of naturally occurring organic acids and phenolic compounds. TTA ranged from 0.86 to 1.17%. Compared with the control (0.92%), TTA decreased slightly at 2-4% MSKP but increased markedly at 6% (1.17%) and remained relatively high at 8% (1.04%). The higher acidity at greater MSKP levels is likely attributable to the increased incorporation of organic and phenolic acids. Unlike pH, TTA showed the total acid content and is less influenced by buffering constituents, explaining the observed differences between the two parameters. MSKP fortification produced only minor changes in pH while moderately increasing TTA at higher substitution levels, suggesting enhanced acid content without compromising product quality. Such trends have also been reported in functional snacks enriched with fruit by-products and seed derived ingredients (Singh *et al.*, 2015).

3.6. Texture attributes

The incorporation of MSKP significantly influenced the textural properties of snacks as presented in Figure 5. Fracturability decreased from 2.65 to 2.16 N with increasing MSKP beyond 2%, indicating progressive weakening of the crisp structure. The initial improvement at low substitution

Table 3. Effect of mango seed kernel powder (MSKP) fortification on acidity profile of snack formulations

MSKP Fortification Levels (%)	pH	Total Titratable Acidity (%)
0	5.79 ± 0.01 ^d	0.92 ± 0.01 ^e
2	5.86 ± 0.01 ^c	0.88 ± 0.01 ^d
4	5.95 ± 0.01 ^a	0.86 ± 0.01 ^e
6	5.69 ± 0.01 ^e	1.17 ± 0.01 ^a
8	5.91 ± 0.01 ^b	1.04 ± 0.01 ^b

(2% MSKP) suggests enhanced structural integrity, whereas higher MSKP levels likely disrupted starch network formation due to increased dietary fiber, reducing the force required for fracture. Toughness generally increased with MSKP incorporation, rising from 0.42 kg·s in control to 0.59 kg·s at 8% MSKP. This increase reflects the formation of a denser, less expanded matrix resulting from the fiber-rich composition of MSKP, which enhanced resistance to fracture. Crispness improved at moderate fortification levels, increasing from 5.48 in the control to 6.16 at 4% MSK, but declined to higher incorporation (4.73 at 6% MSKP). The reduction in crispness consists of decreased expansion and increased bulk density, producing a less porous cellular structure. Similar effects of fiber enrichment

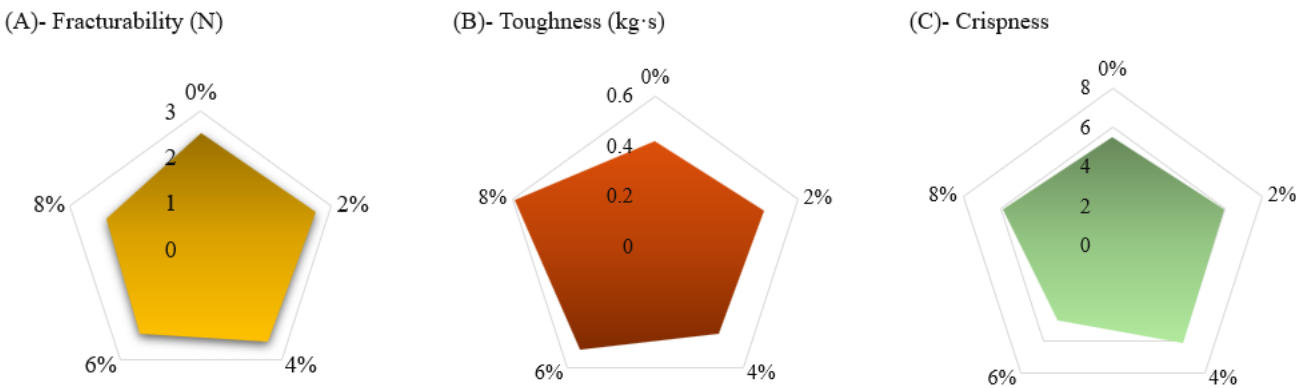


Figure 5. Texture profile of snacks fortified with different levels of MSKP: (A) Fracturability, (B) Toughness, and (C) Crispness

on snack texture have been widely reported. Moderate MSKP incorporation (2-4%) improved or maintained desirable textural characteristics, whereas higher levels (6-8%) produced denser crisps with lower fracturability, greater toughness, and reduced crispness. These findings suggest that limited MSKP substitution offers the optimal balance between nutritional enhancement and textural quality (Singh *et al.*, 2015).

3.7. In vitro starch digestibility and estimated glycemic index

MSKP fortification significantly modified the in-vitro starch digestibility profile of the snacks, as shown in Figure 6, with reductions in estimated glycemic index (eGI) and rapidly digestible starch (RDS), accompanied by increases in slowly digestible starch (SDS) and resistant starch (RS). The eGI decreased progressively from 35.41 in the control to 31.55 at 8% MSKP, indicating a lower predicted glycemic potential based on the in vitro starch hydrolysis response. Similarly, RDS decreased from 77.05% to 64.09%, whereas SDS increased from 8.98% to 17.99% to 8% MSKP. RS increased to a maximum of 22.76% at 6% MSKP before declining slightly at higher MSKP levels. These changes may be associated with the dietary fiber and polyphenolic constituents of MSKP, which can restrict enzyme accessibility and influence starch hydrolysis. Comparable interactions between plant-derived bioactive compounds, dietary fiber, and starch digestibility have been reported by

Cui *et al.* (2024). Overall, MSKP incorporation reduced the in-vitro estimated glycemic potential of the snacks by decreasing eGI and RDS while increasing SDS and RS, indicating an improved in-vitro starch digestibility profile.

3.8. Color characteristics

MSKP fortification significantly influenced the color attributes of snacks as presented in Table 4, affecting lightness (L^*), redness (a^*), yellowness (b^*), and overall color difference (ΔE). These changes are primarily attributed to the intrinsic pigments and polyphenol-rich composition of MSKP, together with non-enzymatic browning during processing. Lightness (L^*) decreased progressively from 82.65 in the control to 72.24 at 8% MSKP, indicating a darker product with increasing fortification. Redness (a^*) increased slightly from 15.76 in the control to 16.19 at 2% MSKP but declined to higher substitution levels, reaching 9.71 at 8% MSKP. Similarly, yellowness (b^*) increased slightly from 27.11 in the control to 28.57 at 2% MSKP but subsequently decreased to 18.90 at 8% MSKP, suggesting that the darker pigments of MSKP progressively masked the native red and yellow hues of the formulation. The observed color changes are consistent with Maillard reactions and the oxidation of phenolic compounds, which enhance brown pigment formation during thermal processing. Similar trends have been reported in snack products enriched with fruit seed flours and other polyphenol-rich plant ingredients (Bows &

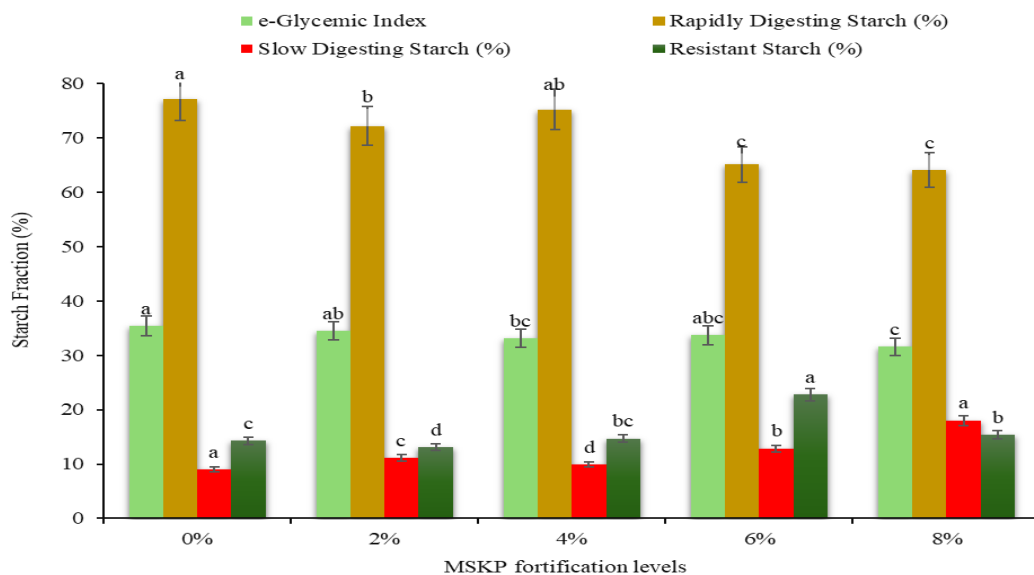


Figure 6. Estimated glycemic index and starch digestibility profile of snacks fortified with different levels of

Table 4. Effect of mango seed kernel powder (MSKP) fortification on the color characteristics of snack formulations

MSKP Fortification Levels (%)	L*	a*	b*	ΔE
0	82.65 ± 0.18 ^a	15.76 ± 0.09 ^b	27.11 ± 0.15 ^c	0.00 ± 0.00 ^c
2	82.15 ± 0.20 ^a	16.19 ± 0.11 ^a	28.57 ± 0.18 ^a	1.60 ± 0.12 ^d
4	79.59 ± 0.22 ^b	10.27 ± 0.08 ^c	20.17 ± 0.14 ^b	9.36 ± 0.25 ^c
6	76.12 ± 0.19 ^c	10.07 ± 0.07 ^c	19.85 ± 0.12 ^b	11.30 ± 0.28 ^b
8	72.24 ± 0.24 ^d	9.71 ± 0.06 ^d	18.90 ± 0.10 ^c	14.57 ± 0.30 ^a

Dimitrakis, 2016). Color difference (ΔE) increased progressively from 0.00 in the control to 1.60, 9.36, 11.30, and 14.57 at 2%, 4%, 6%, and 8% MSKP, respectively, indicating increasingly perceptible color differences with increasing MSKP incorporation. Increasing MSKP incorporation progressively darkened snacks and altered their chromatic attributes, demonstrating the combined effects of MSKP pigmentation and processing-induced browning.

3.9. Sensory acceptability

MSKP fortification significantly influenced the sensory characteristics as shown in Figure 7, including appearance, crunchiness, taste, mouthfeel, flavor, and overall acceptability. Moderate incorporation (2-4%) maintained or improved sensory quality, whereas higher substitution levels (6-8%) reduced consumer preference. 2% MSKP

formulation received the highest scores for appearance (7.3), flavor (7.0), taste (6.9), mouthfeel (6.9), and overall acceptability (6.9), while maintaining crunchiness comparable to the control. These findings indicate that low-level MSK incorporation enhanced product appeal without adversely affecting texture or palatability. Beyond 2% MSKP, sensory scores declined progressively. The reduction in appearance was consistent with instrumental color measurements showing decreased lightness (L*), while lower crunchiness showed reduced expansion and increased product density caused by the higher dietary fiber content of MSKP. Similarly, declines in taste and flavor at higher fortification levels are likely associated with the increased concentration of phenolic compounds and tannin-like constituents, which may impart slight bitterness and astringency. Mouthfeel also deteriorated with increasing

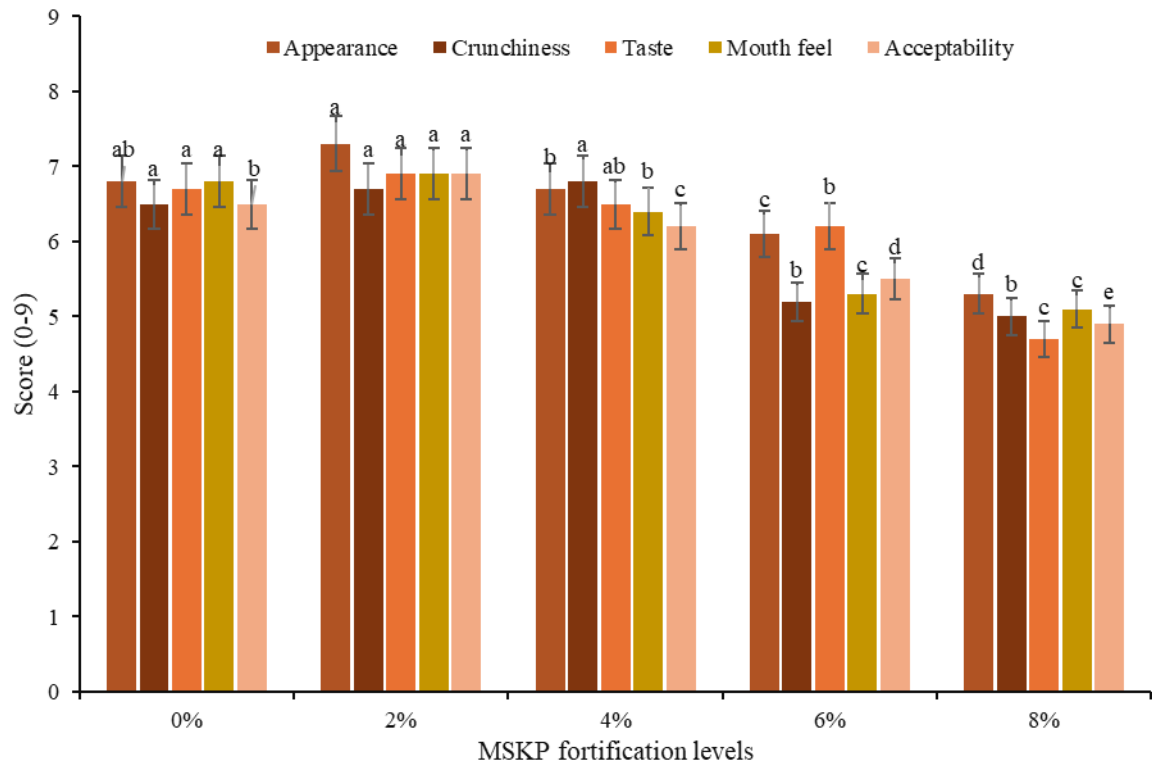


Figure 7. Effect of MSKP fortification on the sensory properties of snacks, including appearance, crunchiness, taste, mouthfeel, flavor, and overall acceptability

MSKP, likely due to the formation of a denser and less porous structure. 2-4% MSKP provided the best balance between enhanced nutritional value and consumer acceptability, whereas higher incorporation levels adversely affected sensory quality. These results suggest that moderate MSKP fortification is optimal for developing nutritionally enriched snacks with desirable sensory attributes (Cui *et al.*, 2024).

Conclusion

The current study demonstrated the potential utilization of agro-industrial by-products, specifically mango seed kernel powder (MSKP) and eggshell powder (ESP), in the formulation of a nutrient-dense snack with low *in vitro* estimated glycemic index (e-GI). By incorporating MSKP and ESP into a mung bean–mango pulp-based foamed snack system, the physical, pasting, textural, and nutritional properties of the product were significantly modified. The addition of MSKP increased total dietary fiber content (up to 6.30%) and total calcium content (up to 79.93 mg/100 g) while maintaining protein levels (17.67-18.93%). The presence of MSKP fiber and polyphenolic constituents modified *in vitro* starch digestibility by reducing the estimated glycemic index (e-GI from 35.41 to 31.55) and rapidly digestible starch (RDS), alongside concurrent increases in slowly digestible starch (SDS) and resistant starch (RS). Although higher substitution levels (6-8%) led to reduced matrix expansion, increased bulk density, and lower flavor scores, an incorporation rate of 2-4% MSKP provided an optimal balance between nutritional enhancement, structural crispness, and overall sensory acceptability. Overall, this dual byproduct enrichment strategy presents a promising approach for developing functional convenience foods with reduced *in vitro* glycemic response. Future studies incorporating *in vivo* clinical trials, gastrointestinal digestion models to assess actual calcium bioavailability, and long-term shelf-life evaluation are recommended to validate the physiological health benefits and storage stability of the optimized formulations.

Ethical Approval

Not applicable

Conflict of Interest

The authors declare no conflict of interest.

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Author Contributions

Muhammad Rehan Arif: Conceptualization, methodology, research trials, manuscript writing. Rakhshanda Hafeez: Conceptualization, data analysis, supervision, validation, manuscript writing, review and editing. Hafiza Ammara Shabbir: Software, data analysis, data curation. Kinza Fatima: Validation, manuscript writing and editing. Saria Yousaf: Validation, review and editing. Ayesha Usman: Validation, manuscript writing, review and editing. Arawat Fatima: Manuscript writing, review and editing. Anum Urooj: Data curation, validation, manuscript writing, review and editing. Muhammad Asif: Data curation, validation, manuscript review and editing. All authors have read and approved the final manuscript.

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