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RESEARCH

# Low Moisture Extrusion of Intermediate Wheatgrass-Pea Starch Blends: Production and Characterization of Ready-to-Eat Extruded Snacks

**Hazrat Usman**[1] · **Cecia Flores-Sanchez**[1] · **George Amponsah Annor**[1]

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**Abstract**
Intermediate wheatgrass [IWG; *Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey], enriched with protein and dietary fiber, has the potential to deliver both food and ecosystem service benefits. However, its lower starch content limits expansion of the extrudates during extrusion, reducing its suitability for puffed ready-to-eat (RTE) snacks. Pea starch, a by-product in pea protein production, can enhance functional attributes of extruded products. Therefore, this systematic study was conducted to optimize the extrusion parameters to produce RTE snacks through a co-rotating twin-screw extruder to meet the increasing demand for nutritious novel foods. Box-Behnken design coupled with response surface methodology was used to investigate the effects of pea starch percentage, feed moisture, screw speed and barrel temperature on product responses (expansion ratio, bulk density, hardness, crispiness, color (L*), water absorption index, water solubility index) and processing response (specific mechanical energy) whose value varied from 1.08 to 2.16, 0.13 to 0.34 g/cm$^3$, 30.33 to 109.74 (N), 284.68 to 751.43 N.s, 72.71 to 80.55, 4.49 to 6.59 g/g, 21.45 to 35.91% and 586.40 to 1132.09 kJ/Kg respectively. Response surface regression models were established to determine the response variables. Regression models for all the responses were highly significant ($p < 0.01$) with coefficient of determination ranged from 0.62 to 0.98. The optimum conditions obtained by multi-response optimization for the development of RTE extruded snacks were IWG flour to pea starch ratio (46:54), feed moisture 19.57%, screw speed 241 rpm and barrel temperature 131 °C. This paper therefore explores the optimization of processing conditions for the development of RTE extruded snacks from IWG-pea starch blends.

**Keywords** Perennial grains · Sustainable agriculture · Optimization · Extrusion · Thermal processing · Intermediate wheatgrass · Pea starch

## Introduction

Worldwide, the majority of cropland is occupied by annual crops, which provide approximately 50% of global caloric intake, but are associated with several environmental problems, including water pollution, soil erosion, and loss of animal habitats (Kearney, 2010; Monfreda et al., 2008). An important strategy to lessen these environmental impacts is the development of perennial crops (Glover et al., 2010). Because of their extensive and deep root systems, which improve resilience to water scarcity by reaching the underground stored water. Perennial crops also support sustainable agroecosystems by minimizing soil erosion, cycling nutrients, and sequestering carbon through continuous deep roots activity (Clément et al., 2022; Förster et al., 2025).

A significant advancement in sustainable agriculture is achieved through the development of Intermediate wheatgrass (*Thinopyrum intermedium*, IWG), commercially known as Kernza® by the Land Institute in Kansas (USA). It is the first perennial grain crop commercialized in the US to provide both forage and grain (Ginot et al., 2024; Law et al., 2022). Like wheat, rye, and barley, IWG is a member of the Triticeae tribe within the Poaceae grass family and is related to wheat (Boakye et al., 2023a, 2023b; Cetiner et al., 2023). In 1932, IWG was introduced from the Russian region of Miakop for the control of soil erosion and forage. IWG gained attention for its

✉ George Amponsah Annor
gannor@umn.edu

[1] Department of Food Science and Nutrition, University of Minnesota, 1334 Eckles Avenue, Saint Paul, MN 55108, USA

high biomass yield and tolerance to frost and drought. Its agronomic adaptability supports dual-use systems, offering grains and straw harvest in summer, as well as spring and fall forage through regrowth (Favre et al., 2019; Rusch et al., 2025). This dual system may offer potential for diversifying farmers' income, but its overall productivity and profitability remain under evaluation (Clément et al., 2022). In the 1980 s, efforts began to domesticate IWG for grain production, with significant breeding advancements made over the past two decades (DeHaan et al., 2018). A major milestone was achieved in 2020 when the University of Minnesota released the first grain-producing IWG cultivar (Bajgain et al., 2020). Although globally, most of the food and feed is supplied by annual grains, currently across North America and Europe, several breeding programs are working on enhancing IWG's viability as a commercial grain crop contributing to develop perennial grains that support both food security and ecosystem services such as carbon sequestration, nitrate leaching reduction, and erosion control (Crain et al., 2020).

In addition to ecological advantages, IWG exhibits nutritional and functional properties. It contains higher protein (50%), dietary fiber (129%), ash (65%), calcium (267%), and selenium (492%), along with elevated riboflavin and folate, though niacin is lower as compared to traditional whole wheat flour (Craine & DeHaan, 2024; Schendel et al., 2015). Functionally, IWG starch and dough properties resemble those of wheat. Rheological analysis revealed that IWG protein forms a gas holding network, supporting its potential in breadmaking (Grandal et al., 2025). IWG has been explored for the food application (Boakye et al., 2023a, 2023b).

Starch plays a key role in extrudate expansion through its gelatinization, with higher starch content typically resulting in improved expansion ratios (Van Hoan et al., 2010). IWG has more protein and lower starch content, which results in less expansion of the extrudates (Boakye et al., 2022; Tyl & Ismail, 2019). In our research, we incorporated different levels of pea starch into IWG whole flour to get more expansion of the extrudates.

Incorporating legumes like pea (*Pisum sativum* L.) as a key ingredient in the formulation of snack food can enhance the nutritional value by increasing protein and fiber content. Pea-based expanded snacks have been developed using different combinations of pea flour, fiber, and starch, along with varied extrusion temperatures. Pea starch with other ingredients in combination can further enhance the sensory attributes of the snacks (Maskus & Arntfield, 2015; LUO, 2019).

In response to increasing consumer interest in plant-based proteins because of their high nutritional value and affordability, the food industry scales up pea protein concentrates and isolates production, with a market of 34.8 million USD in 2020. Consequently, significant amounts of pea starch are produced as a by-product, highlighting the need for value-added applications of pea starch (Rangira et al., 2020).

Pea starch makes up about 44.7% to 50.3% of whole pea flour and is composed of two polysaccharides: amylose and amylopectin (Rangira et al., 2020). The high amount of amylose in pulse starch imparts exceptional functional properties including high gelatinization temperature, rapid retrogradation, resistance to shear thinning, and strong gel elasticity. These properties make it ideal for products like starch noodles commonly made by extruding dough formed from native and pregelatinized starch (Wang et al., 2014). Pea starch can be a viable alternative to traditional starch sources like wheat in animal feed, especially for pigs (Thingnes et al., 2013).

Snacks are commonly referred to as small portions of food eaten between meals, with definitions varying by timing, quantity, or type (Ali et al., 2024). Extruded snacks, such as puffed ready-to-eat (RTE) cereals, have gained widespread popularity globally, particularly among children (Bhat et al., 2019; *Annex 6—Glossary | Food Standards Agency*, 2025). In most snack products, formulations are cereals like wheat, corn, and rice, with some portion of oats, potatoes, and other ingredients typically used (Nor et al., 2013; Sharma & Gujral, 2013).

RTE snacks have become essential to many individuals, and the demand for these snacks is growing as consumers desire convenience, texture appealing, and healthy products (Brennan et al., 2013; Chadha et al., 2021). The global market for extruded snacks remains strong, valued at USD 71.5 billion in 2024 and is forecasted to reach USD 104.8 billion by 2030, growing at a CAGR of 6.6% (Brennan et al., 2013; ltd, 2025).

Extrusion technology is widely used in producing cereal-based RTE snacks due to its ease of operation and ability to create diverse, appealing textures and shapes (Brennan et al., 2013). Extrusion technology is widely used to manufacture several food products like pasta, noodle snacks, breakfast cereals, baby food, meat analogues, pet foods, texturized vegetable proteins, and more (Ali et al., 2024; Boakye et al., 2023a, 2023b; Geetha et al., 2014; Wang et al., 2012). As a result, extrusion cooking has become an extensively accepted industrial technology across food and feed sectors, with market demand projected to reach USD 99.7 billion by 2026 (Dey et al., 2024; *Food Extrusion Market*, 2015).

Twin-screw extrusion (TSE) is preferred in the food industry due to its automated control, energy efficiency, cost-effectiveness, high capacity, continuous operations, and its flexibility in adjusting screw profile, barrel temperature, and rotational speed tailored to specific formulations (Dey et al., 2024; Wang et al., 2019). Extrusion is a high-temperature and short-time process that involves the flow of one or more polymer melts and the integration of multiple operations such as mixing, kneading, shearing, and cooking the raw

materials. The mixed ingredients are forced through a die of specific size and shape, then cut into a range of food products (Bordoloi & Ganguly, 2014).

During extrusion processing, parameters like barrel temperature, moisture of the feed, materials composition, screw speed, and its configuration affect the quality of extrudates (Brennan et al., 2013). Extrusion cooking is a multi-step, multi-functional, and thermal/mechanical process that affects nutritional quality, degrades some components; it also offers benefits such as starch gelatinization, destruction of anti-nutritional factors, increased soluble fiber, and reduced lipid oxidation (Choton et al., 2020; Singh et al., 2007). However, it may also reduce levels of resistant and slowly digestible starch (Boakye et al., 2023a, 2023b).

The expansion and crispness achieved through temperature and pressure differentials (Brennan et al., 2013). Low moisture (below 30%) extrusion is widely used in the production of expanded snacks (Beck et al., 2017). The expansion of extrudates, primarily driven by starch transformation, enhances the crispiness of products and attracts consumers (Brennan et al., 2013).

The objective of our research was to produce expanded ready-to-eat snacks using whole-grain flour from intermediate wheatgrass blended with various levels of pea starch. Response surface methodology (RSM) was employed to evaluate the physical and functional properties of IWG-pea starch blends extrudates and optimize processing conditions to scale up the extrusion parameters.

## Materials and Methods

### Materials

Intermediate wheatgrass [IWG; Thinopyrum intermedium (Host) Barkworth & D.R. Dewey] grains known as Kernza® variety MN Clearwater were supplied by Perennial Pantry, SBC (12,651 Zenith Ave. S, Ste. 107, Burnsville, MN 55337). The grains were stored at 4 °C to preserve quality. Milling was conducted using a hammer mill equipped with sieve number 40 (sieve size ~ 0.5 mm) in the Department of Food Science and Nutrition at the University of Minnesota. The grains were ground into whole flour, which included all components of the kernel. The IWG whole flour was blended with different levels of pea starch and used for extrudate production. IWG whole flour typically contains approximately 20.2% protein, 48.9% starch, 19.9% dietary fiber, 3.6% total lipid, and 2.8% ash (Boakye et al., 2023a, 2023b).

Pea starch (Item No. PS85-B), preferred for extrusion applications, was obtained from PURIS (811 Glenwood Ave, Suite 110, Minneapolis, MN 55405, USA). It was used as a key ingredient in formulating blends (30%, 50% and 70%) with IWG-flour for extrusion processing. A twin shell dry blender (The Patterson-Kelley Co., Inc. East Stroudsburg, Pennsylvania) was used to thoroughly mix the IWG-pea starch blends for 10 min to get uniform mixture. Pea starch shows genotype-dependent amylose content, ranging from 29 to 49% in smooth peas to 60 to 78% in wrinkled peas. It also exhibits distinct digestibility fractions, with RDS (16 to 23%), SDS (33 to 37%), and RS (43 to 47%) (Johansson et al., 2026).

### Experimental Design

A Box-Behnken design, coupled with response surface methodology (RSM) was developed by Stat-Ease® 360 software (Version 24, Stat-Ease, Inc., Minneapolis, MN, USA). The factors included pea starch percentage as $X_1$, feed moisture percentage as $X_2$, screw speed as $X_3$ and barrel temperature °C as $X_4$. The lowest, highest, and mid values of the variables were coded as − 1 and + 1, respectively, and the mid value coded as 0 see Table 1.

The experimental ranges were determined through preliminary trials performed following the factors' ranges applied by Boakye et al. (2022) to ensure continuous, safe and effective extrusion operation. Pea starch below 30% had negligible impacts on the extrudates, while above 70% could hinder the effect and properties of the main ingredient, IWG whole flour, in the final products. Feed moisture below 19% created high load (torque) and excessive pressure in extruders, which led the machine to stop, whereas above 23% feed moisture prevented product expansion. Screw speeds less than 200 rpm and above 300 rpm resulted in undesirable products. Barrel temperatures below 120 °C provided uncooked, hard and undesirable exudates, while those above 150 °C led to material burning. The results of Boakye et al. (2022) revealed that 28% moisture, 400 rpm, and 170 °C, expansion was minimal (expansion ratio = 0.97 ± 0.01). A Box-Behnken design coupled with response surface methodology (27

**Table 1** Independent variables and their corresponding coded and actual levels for IWG-pea starch extrusion

| Independent variables | Symbols | Coded levels | | |
|---|---|---|---|---|
| | | − 1 | 0 | + 1 |
| | | Actual levels | | |
| Pea starch (%) | $X_1$ | 30 | 50 | 70 |
| Moisture (%) | $X_2$ | 19 | 21 | 23 |
| Screw speed (rpm) | $X_3$ | 200 | 250 | 300 |
| Temperature (°C) | $X_4$ | 120 | 135 | 150 |

− 1 = lowest level of independent variables, 0 = midst level of independent variables, and + 1 = highest level of independent variables

Abbreviations: *IWG* intermediate wheatgrass, *rpm* revolutions per minute

**Table 2** Temperature setting in the six heating zones of the extruder

| Barrel end temperature [℃] | Zone 1[℃] | Zone 2[℃] | Zone 3[℃] | Zone 4[℃] | Zone 5[℃] | Zone 6[℃] |
|---|---|---|---|---|---|---|
| 120 | 50 | 80 | 120 | 120 | 120 | 120 |
| 135 | 50 | 80 | 120 | 135 | 135 | 135 |
| 150 | 50 | 80 | 120 | 150 | 150 | 150 |

variable combinations with three center points) was applied to evaluate the interactive effects of pea starch content, feed moisture, screw speed, and barrel temperature at a constant feed rate of 2.5 kg/h on product functional properties as shown in Table 3. The experimental design shown in Table 3 is ran in duplicate.

## Extrusion of IWG-Pea Starch Blends

A co-rotating twin-screw (Brabender R © TwinLab-F20/40) extruder with an 800 mm screw length and 20 mm diameter (resulting in an L/D ratio of 40:1) was used for extruding IWG flour-pea starch blends extrusion. The extruder comprised six

**Table 3** Variable combinations as determined using a Box-Behnken design coupled with response surface methodology (RSM)

| Run | Variables code | | | | Actual variables | | | |
|---|---|---|---|---|---|---|---|---|
| | $X_1$ | $X_2$ | $X_3$ | $X_4$ | Pea starch (%) | Feed moisture (%) | Screw speed (rpm) | Temperature (℃) |
| 1 | −1 | +1 | 0 | 0 | 30 | 23 | 250 | 135 |
| 2 | 0 | −1 | 0 | −1 | 50 | 19 | 250 | 120 |
| 3 | +1 | +1 | 0 | 0 | 70 | 23 | 250 | 135 |
| 4 | 0 | 0 | −1 | −1 | 50 | 21 | 200 | 120 |
| 5 | −1 | 0 | 0 | +1 | 30 | 21 | 250 | 150 |
| 6 | 0 | 0 | +1 | +1 | 50 | 21 | 300 | 150 |
| 7 | +1 | 0 | 0 | +1 | 70 | 21 | 250 | 150 |
| 8 | 0 | −1 | +1 | 0 | 50 | 19 | 300 | 135 |
| 9 | 0 | +1 | 0 | −1 | 50 | 23 | 250 | 120 |
| 10 | +1 | 0 | 0 | −1 | 70 | 21 | 250 | 120 |
| 11 | −1 | 0 | +1 | 0 | 30 | 21 | 300 | 135 |
| 12 | 0 | 0 | +1 | −1 | 50 | 21 | 300 | 120 |
| 13 | 0 | 0 | −1 | +1 | 50 | 21 | 200 | 150 |
| 14 | 0 | −1 | 0 | +1 | 50 | 19 | 250 | 150 |
| 15 | 0 | +1 | −1 | 0 | 50 | 23 | 200 | 135 |
| 16 | 0 | +1 | 0 | +1 | 50 | 23 | 250 | 150 |
| 17 | +1 | 0 | −1 | 0 | 70 | 21 | 200 | 135 |
| 18 | 0 | 0 | 0 | 0 | 50 | 21 | 250 | 135 |
| 19 | 0 | 0 | 0 | 0 | 50 | 21 | 250 | 135 |
| 20 | +1 | −1 | 0 | 0 | 70 | 19 | 250 | 135 |
| 21 | −1 | −1 | 0 | 0 | 30 | 19 | 250 | 135 |
| 22 | 0 | −1 | −1 | 0 | 50 | 19 | 200 | 135 |
| 23 | −1 | 0 | 0 | −1 | 30 | 21 | 250 | 120 |
| 24 | −1 | 0 | −1 | 0 | 30 | 21 | 200 | 135 |
| 25 | +1 | 0 | +1 | 0 | 70 | 21 | 300 | 135 |
| 26 | 0 | 0 | 0 | 0 | 50 | 21 | 250 | 135 |
| 27 | 0 | +1 | +1 | 0 | 50 | 23 | 300 | 135 |

$X_1$ = pea starch, $X_2$ = feed moisture, $X_3$ = screw speed and $X_4$ = extrusion temperature. − 1 = lowest level of independent variables, 0 = midst level of independent variables and + 1 = highest level of independent variables

Abbreviations: *rpm* revolutions per minute

heating zones, which were controlled independently. The first three heating zones of the extruder were set at 50 °C, 80 °C, and 120 °C. In comparison, the set temperatures in the last three zones (4, 5, and 6) were the same according to the experimental design (Table 2). Screw speed ranging from 200 to 300 rpm was regulated according to the experimental design (Table 3). The screw was designed in such a way that the first section contained conveying elements, with the next containing both conveying and kneading elements. Finally, the high shear section contained conveying, reverse conveying, and kneading elements as represented in Fig. 1. Desired moisture (19%, 21%, and 23%) of the feed was achieved by injecting calculated amounts of water directly into the barrel using a peristaltic pump. The raw material was fed into the extruder using a twin-screw feeder (DDSR 20, Brabender Technologie, Germany). The feed rate was controlled by screw speed in gravimetric mode, enabling continuous monitoring and precise control of mass flow. A constant feed rate of 2.5 kg/h was maintained throughout the experiment. Approximately 1–1.5 kg of raw material was used per treatment. A 5 mm circular die was fitted at the exit of the extruder to shape the extrudates. After extrusion, extruded samples were dried at 50 °C for 18 h, packed in airtight zip-lock bags, and subsequently stored under refrigerated conditions (~4 °C) until further analysis.

## Expansion Ratio

A digital Vernier caliper (Toolshop®, Menard Inc., Eau Claire, WI, USA) was used to precisely measure the diameter of the ten randomly selected exudates from each experimental run. The expansion ratio was then calculated by dividing the cross-sectional diameter of the extrudates by the diameter of the circular die, following the method as described by Boakye et al. (2022).

$$\text{Expansion ratio} = \frac{\text{Average diameter of the extruadates (mm)}}{\text{Average diameter of the die (mm)}} \quad (1)$$

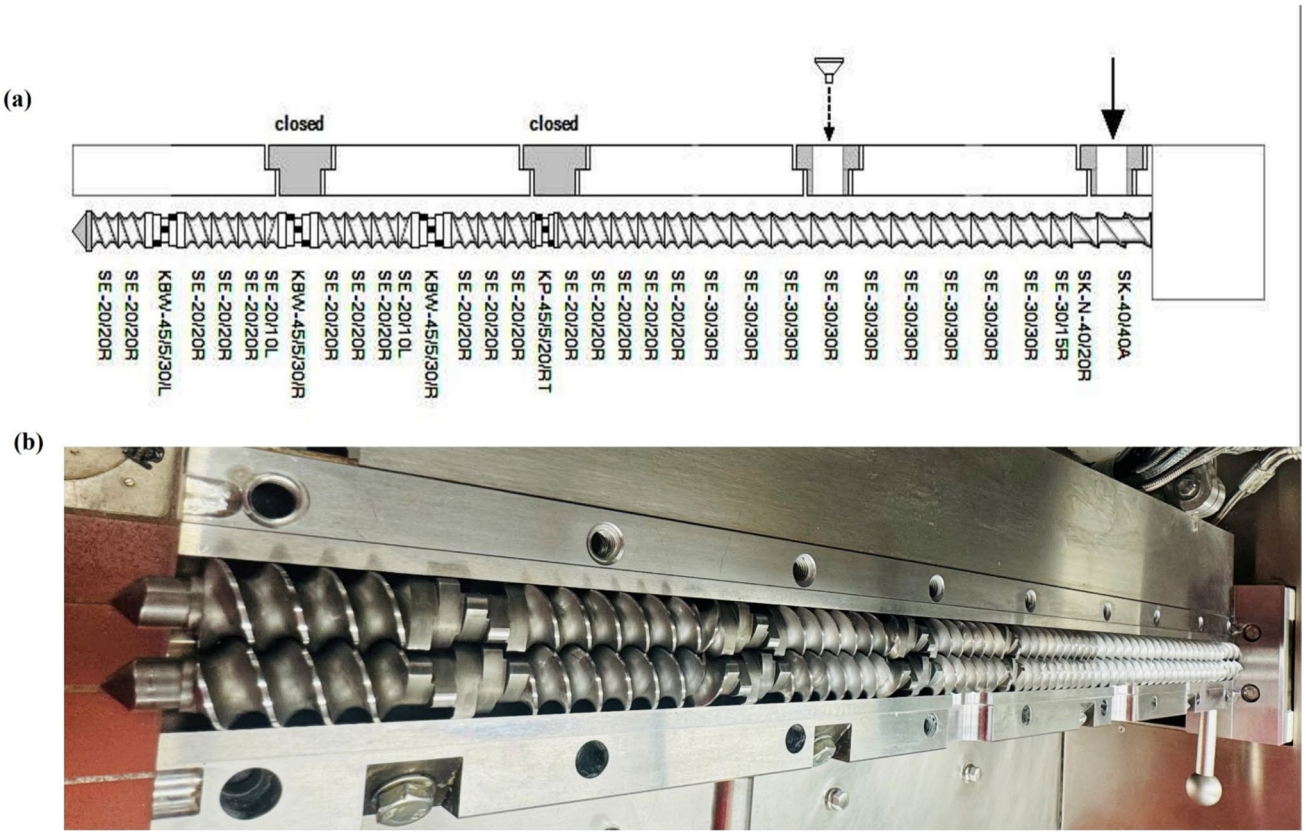



**Fig. 1** **a** Schematic representation of the screw configuration used in the extrusion processing. The configuration includes forward and reverse conveying screw elements, kneading blocks for mixing and shear development, and screw tips for final discharge. Note: SE, normal screw profile, SK, thrust edge profile SK-N, thrust-edge-to-normal profile, first number, pitch in mm; second number, length in mm; R, conveying, L, reverse conveying; A, feed element with undercut on the gear side; KB, kneading block; KBW, kneading block with a wide land; KP, kneading block with half disk width on both sides; first number, angular offset between the disks (°); second number, disks length in mm; third number, length in mm; T, twist; N, neutral kneading block. **b** Picture of the Brabender® Twin-Screw used in extrusion processing, Department of Food Science and Nutrition, University of Minnesota

## Bulk Density

The glass beads displacement method described by Rangira et al. (2020), with some modification (Rape seeds instead of glass beads; they provide better void filling for improved accuracy while minimizing structural damage due to their lighter weight), was used to determine the bulk density of the extrudates. Bulk density was calculated by dividing the mass of the extrudates by the recorded displaced volume.

$$\text{Bulk density} = \frac{\text{Mass of the extruadates (g)}}{\text{Volume of the displaced rape seeds by extrudates (cm3)}} \quad (2)$$

## Water Absorption Index (WAI) and Water Solubility Index (WSI)

Water absorption index and water solubility index were determined according to the method described by (Boakye et al., 2022). UDY cyclone sample mill (Udy Corp., Fort Collins, CO, USA) equipped with a 0.5 mm screen was used to mill the dried extruded samples. For each analysis, 2 g of powdered sample were thoroughly mixed with 20 ml of distilled water using a vortex and agitated for 30 min at room temperature using G24 environmental incubator shaker (New Brunswick Scientific Co., Inc. Edison N.J., USA) to ensure uniform hydration. The mixture was then centrifuged at 3000 g for 10 min to separate the soluble and insoluble fractions. The resulting supernatant was carefully collected in pre-weighted aluminum pans and dried at 135 °C for 2 h to determine the dry solids. WAI was calculated by determining the weight of the hydrated sediment residue remaining after centrifugation, while WSI was expressed as the percentage of dried solids in the supernatant relative to the original sample weight. This approach enables the assessment of the swelling capacity and solubility behavior of the samples under aqueous conditions.

$$\text{Water absorption index (g/g)} = \frac{\text{Weight gain by gel (g)}}{\text{Dry weight of extrudate sample (g)}} \quad (3)$$

$$\text{Water solubility index (\%)} = \frac{\text{Weight of dissolved solids in supernatant}}{\text{Weight of dry solids}} \times 100 \quad (4)$$

## Hardness and Crispiness

The hardness of the extrudates was assessed using TA-XT2i Texture Analyzer (Stable Micro Systems Ltd., Godalming, Surrey, UK), as described by Boakye et al. (2022), with slight modifications to the testing parameters. All samples were dried overnight at 50 °C to equilibrate the moisture content of the extrudates before texture analysis. A 13 mm cylindrical probe was employed to perform a compression test under controlled conditions. The analysis was conducted with a 2 mm/s pretest speed, followed by both test and post-test speeds set at 0.4 mm/s, 50% strain, 5-s hold time, and a 5 g trigger force. The instrument's Exponent software was used to record the force hardness values in Newtons and crispiness (number and intensity of fracture events) values in Newton.

## Color

A Chroma Meter (CR-200; Minolta, Tokyo, Japan) was used to determine the color of milled extrudates with a method reported by Zhang et al. (2020). The color parameter (L*) was noted. This parameter L* indicates brightness ranging from 0 = black to 100 = white.

## Specific Mechanical Energy (SME)

The specific mechanical energy was calculated from torque N.m given by the extruder software using the data of the power consumed per unit of time and the total feed input (solids + water) (Heredia-Olea et al., 2020). During extrusion, real time data such as zone temperature, motor torque, and pressure were continuously recorded using a data acquisition system coupled with the Brabender® extruder. One data point was collected per second, and average values for torque (approximately 20–36 N.m) were derived from 20 randomly selected readings under steady state conditions (Boakye et al., 2023a, 2023b). Specific mechanical energy (SME, kJ/kg) was calculated from screw speed, measured torque and power as described by Kristiawan et al. (2018).

$$\text{SME} = \frac{\frac{N}{Nmax} \times \tau - \tau empty/100}{Q} \times Pmax \times 3600 \quad (5)$$

where N and $N_{max}$ represent the actual and maximum screw speeds, while τ and $\tau_{empty}$ denote the measured torque under loaded and no-load conditions, respectively. The maximum power of the extruder is Pmax and Q is the feed flow rate (kg/h).

### Statistical Analysis

A Box-Behnken design coupled with response surface methodology (Table 3) was applied to evaluate the interactive effects of four factors (pea starch content, feed moisture, screw speed, and barrel temperature) at a constant feed rate of 2.5 kg/h on product functional properties. Stat-Ease® 360 software (Version 24, Stat-Ease, Inc., Minneapolis, MN, USA) was used for data analysis and graphical presentation. JMP® Student Edition (Version 18, JMP Statistical Discovery LLC, Cary, NC, USA) was used for graphical presentation of the optimized data. The effects of process conditions on product responses and process response were evaluated. The experimental data obtained was fitted into quadratic equations, as shown in Eq. 6.

$$Y = A_0 + A_1X_1 + A_2X_2 + A_4X_3 + A_4X_4 + A_{12}X_1X_2 + A_{13}X_1X_3 + A_{14}X_1X_4 + A_{23}X_2X_3 + A_{24}X_2X_4 + A_{34}X_3X_4 + A_{11}X_1^2 + A_{22}X_2^2 + A_{33}X_3^2 + A_{44}X_4^2 \quad (6)$$

where Y denotes the predicted responses (ER, BD, WAI, WSI, Hardness, Crispiness, SME, and Color), $A_o$ is the interception, $A_1$ to $A_4$ are the coefficients of the linear terms, $A_{12}$ to $A_{34}$ represent the coefficients of two-way interaction terms, and $A_{11}$ to $A_{44}$ correspond to the coefficients of the quadratic terms. The coded variables $X_1$, $X_2$, $X_3$, and $X_4$ represent the levels of pea starch, feed moisture, screw speed, and temperature, respectively.

The effects of processing variables were evaluated using analysis of variance (ANOVA), which showed significant differences ($p < 0.05$) among treatment combinations for all responses. Post-hoc comparisons using Fisher's LSD test indicated significant separation of means. All responses varied significantly across treatments, reflecting the influence of processing conditions on extrudate properties. Mean values are presented in Table 4, with different superscript letters indicating significant differences ($p < 0.05$).

### Optimization

After optimizing each individual response numerically, corresponding criteria for both the responses and the independent variables were established to conduct the multi-response optimization using STAT-EASE 360®.

## Results and Discussion

### Response Surface Methodology (RSM)

RSM, a statistical technique that describes the relationship between process variables and product characteristics, was used in this study due to its ability to generate accurate and reproducible second-order models with a minimal number of experimental runs. It is commonly applied to plan a response surface within a specified region of interest, optimize responses, or determine operating conditions that meet target specifications. For each response variable, second-order polynomial regression models were developed to fit the experimental data using STAT-EASE 360®. The experimental results for measured responses are summarized in Table 4. All developed models were statistically significant ($p < 0.05$), while the lack-of-fit tests were not significant ($p > 0.05$), indicating that the models adequately represented the experimental data. Analysis of variance (ANOVA) was conducted to evaluate the significance of individual model terms as represented in Table 5. The coefficient of determination ($R^2$) and adjusted $R^2$ values, predicted $R^2$ followed by adequate precision values for each response variable are shown in Table 4. The $R^2$ values ranged from 0.62 to 0.98 for all responses, indicating strong model reliability. Furthermore, adequate precision of each response model which measures the signal-to-noise ratio and reflects the adequacy of the model in distinguishing meaningful variation from background noise, was calculated to be than 4 which is generally considered acceptable, and this value indicates that the model possesses a sufficiently strong signal (Table 6). Consequently, the model is deemed suitable for exploring and optimizing within the defined design space. To facilitate interpretation, three-dimensional response surface plots were generated to illustrate variations in responses relative to process variables. Optimization was performed under the following constraints: maximizing expansion ratio and crispiness, while minimizing bulk density (BD) and hardness of the extrudates as shown in Figure 9.

### Physical Properties of Extrudates

#### Expansion Ratio (ER)

ER is an important quality indicator for extrudates and RTE puffed snacks, which can affect the texture, lightness, and overall consumer acceptance (Boakye et al., 2022; Chou & Hsu, 2021; Uribe-Wandurraga et al., 2020). Generally, feed moisture content, barrel temperature, and screw speed are factors affecting the ER of the extrudates (Ali et al., 2024;

**Table 4** Experimental values of the response variables from independent variable combinations using Box-Behnken design coupled with response surface methodology (RSM)

| Run | $X_1$ | $X_2$ | $X_3$ | $X_4$ | ER | BD (g/cm$^3$) | WAI (g/g) | WSI (%) | Hardness (N) | Crispiness (N.s) | SME (KJ/Kg) | Color (L*) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | −1 | +1 | 0 | 0 | 1.12$^{a}$ | 0.25$^{cdefg}$ | 5.75$^{hijk}$ | 21.45$^{a\ B}$ | 109.74$^{e\ A}$ | 639.19$^{fgh}$ | 764.40$^{cdef}$ | 76.00$^{bcdefghi}$ |
| 2 | 0 | −1 | 0 | −1 | 2.16$^{i\ A}$ | 0.16$^{abc}$ | 4.81$^{abc}$ | 32.34$^{ijk}$ | 39.25$^{ab}$ | 464.76$^{abcdefg}$ | 1070.91$^{ij}$ | 74.86$^{abcdef}$ |
| 3 | +1 | +1 | 0 | 0 | 1.29$^{ab}$ | 0.22$^{abcdef}$ | 6.30 $^{kl}$ | 23.10$^{abcde}$ | 56.04$^{abc}$ | 394.53$^{abcdef}$ | 793.18$^{defg}$ | 79.68$^{kl}$ |
| 4 | 0 | 0 | −1 | −1 | 1.63$^{cdefghi}$ | 0.29$^{efg}$ | 5.64$^{ghij}$ | 25.99$^{abcdef}$ | 104.70$^{de}$ | 751.43 $^{h\ A}$ | 749.62$^{cde}$ | 74.50$^{abcd}$ |
| 5 | −1 | 0 | 0 | +1 | 1.25$^{ab}$ | 0.21$^{abcde}$ | 5.01$^{abcde}$ | 29.08$^{fghij}$ | 53.53$^{abc}$ | 379.42$^{abcd}$ | 748.06$^{bcde}$ | 74.82$^{abcdef}$ |
| 6 | 0 | 0 | +1 | +1 | 1.17$^{a}$ | 0.17$^{abcd}$ | 4.74$^{abc}$ | 32.92$^{jk}$ | 34.22$^{ab}$ | 293.92$^{a}$ | 946.94$^{hi}$ | 77.69$^{fghijkl}$ |
| 7 | +1 | 0 | 0 | +1 | 1.42$^{abcdef}$ | 0.18$^{abcde}$ | 6.09$^{jkl}$ | 25.76$^{abcdef}$ | 30.33$^{a\ B}$ | 284.68$^{a\ B}$ | 815.83$^{defgh}$ | 78.45$^{hijkl}$ |
| 8 | 0 | −1 | +1 | 0 | 1.91$^{ghi}$ | 0.16$^{abcd}$ | 4.65$^{ab}$ | 32.13$^{hijk}$ | 30.92$^{a}$ | 480.18$^{abcdefg}$ | 1132.09$^{j\ A}$ | 73.33$^{ab}$ |
| 9 | 0 | +1 | 0 | −1 | 1.44$^{abcdef}$ | 0.34 $^{g\ A}$ | 5.14$^{bcdef}$ | 31.00$^{ghij}$ | 100.87$^{de}$ | 664.66$^{gh}$ | 828.72$^{defgh}$ | 76.48$^{cdefghij}$ |
| 10 | +1 | 0 | 0 | −1 | 1.73$^{cdefghi}$ | 0.28$^{efg}$ | 6.08$^{jkl}$ | 22.75$^{abc}$ | 88.73$^{cde}$ | 626.23$^{efgh}$ | 924.34$^{gh}$ | 79.20$^{jkl}$ |
| 11 | −1 | 0 | +1 | 0 | 1.10$^{a}$ | 0.20$^{abcde}$ | 4.87$^{abcd}$ | 28.00$^{fghi}$ | 40.83$^{ab}$ | 325.99$^{ab}$ | 901.40$^{fgh}$ | 74.61$^{abcde}$ |
| 12 | 0 | 0 | +1 | −1 | 1.35$^{abcd}$ | 0.26$^{defg}$ | 4.95$^{abcde}$ | 31.57$^{ghijk}$ | 50.48$^{ab}$ | 413.99$^{abcdef}$ | 1105.47$^{j}$ | 76.38$^{cdefghij}$ |
| 13 | 0 | 0 | −1 | +1 | 1.39$^{abcde}$ | 0.19$^{abcde}$ | 5.44$^{efghi}$ | 26.87$^{bcdefg}$ | 43.59$^{ab}$ | 381.93$^{abcde}$ | 638.76$^{abc}$ | 76.15b$^{bcdefghi}$ |
| 14 | 0 | −1 | 0 | +1 | 1.37$^{abcde}$ | 0.19$^{abcde}$ | 4.57$^{ab}$ | 35.91 $^{k\ A}$ | 33.67$^{ab}$ | 311.61$^{a}$ | 847.03$^{defgh}$ | 77.59$^{efghijkl}$ |
| 15 | 0 | +1 | −1 | 0 | 1.36$^{abcde}$ | 0.33 $^{fg}$ | 5.47$^{fghi}$ | 27.57$^{defgh}$ | 57.98$^{abc}$ | 483.14$^{abcdefg}$ | 609.06$^{ab}$ | 75.55$^{abcdefgh}$ |
| 16 | 0 | +1 | 0 | +1 | 1.23$^{ab}$ | 0.28$^{efg}$ | 5.44$^{efghi}$ | 27.05$^{cdefg}$ | 69.48$^{bcd}$ | 478.75$^{abcdefg}$ | 712.04$^{abcd}$ | 76.95$^{defghij}$ |
| 17 | +1 | 0 | −1 | 0 | 1.8$^{efghi}$ | 0.25$^{cdefg}$ | 6.59 $^{l\ A}$ | 22.90$^{abcd}$ | 52.46$^{abc}$ | 499.93$^{abcdefg}$ | 715.01$^{abcd}$ | 77.95$^{ghijkl}$ |
| 18 | 0 | 0 | 0 | 0 | 1.86$^{fghi}$ | 0.13$^{a\ B}$ | 5.01$^{abcde}$ | 24.99$^{abcdef}$ | 38.09$^{ab}$ | 625.03$^{defgh}$ | 885.02$^{efgh}$ | 75.01$^{abcdefg}$ |
| 19 | 0 | 0 | 0 | 0 | 1.80$^{efghi}$ | 0.15$^{abc}$ | 5.07$^{abcdef}$ | 28.85$^{fghij}$ | 45.086$^{ab}$ | 579.06$^{cdefgh}$ | 895.28$^{fgh}$ | 73.24$^{ab}$ |
| 20 | +1 | −1 | 0 | 0 | 1.80$^{efghi}$ | 0.14$^{ab}$ | 5.90$^{ijk}$ | 27.77$^{efghi}$ | 36.28$^{ab}$ | 376.44$^{abc}$ | 1084.46$^{ij}$ | 80.55 $^{l\ A}$ |
| 21 | −1 | −1 | 0 | 0 | 1.32$^{abc}$ | 0.17$^{abcd}$ | 4.49$^{a\ B}$ | 28.99$^{fghij}$ | 33.70$^{ab}$ | 377.25$^{abc}$ | 890.07$^{fgh}$ | 72.71$^{a\ B}$ |
| 22 | 0 | −1 | −1 | 0 | 1.98$^{hi}$ | 0.16$^{abcd}$ | 4.96$^{abcde}$ | 29.31$^{fghij}$ | 34.32$^{ab}$ | 423.46$^{abcdefg}$ | 834.32$^{defgh}$ | 75.22$^{abcdefg}$ |
| 23 | −1 | 0 | 0 | −1 | 1.08$^{a\ B}$ | 0.21$^{abcde}$ | 4.72$^{ab}$ | 29.00$^{fghij}$ | 54.84$^{abc}$ | 354.23$^{abc}$ | 823.17$^{defgh}$ | 74.58$^{abcde}$ |
| 24 | −1 | 0 | −1 | 0 | 1.34$^{abcd}$ | 0.25$^{bcdefg}$ | 5.05$^{abcde}$ | 22.24$^{ab}$ | 95.66$^{de}$ | 584.62$^{cdefgh}$ | 586.40$^{a\ B}$ | 74.00$^{abcd}$ |
| 25 | +1 | 0 | +1 | 0 | 1.46$^{abcdef}$ | 0.20$^{abcde}$ | 6.06$^{jkl}$ | 24.94$^{abcdef}$ | 44.73$^{ab}$ | 396.11$^{abcdef}$ | 1081.24$^{ij}$ | 79.03$^{ijkl}$ |
| 26 | 0 | 0 | 0 | 0 | 1.78$^{defghi}$ | 0.15$^{abc}$ | 5.10$^{bcdef}$ | 27.01$^{cdefg}$ | 41.56$^{ab}$ | 568.71$^{bcdefgh}$ | 872.08$^{efgh}$ | 73.89$^{abc}$ |
| 27 | 0 | +1 | +1 | 0 | 1.51$^{abcdefg}$ | 0.21$^{abcde}$ | 5.31$^{cdefg}$ | 27.60$^{defgh}$ | 50.15$^{ab}$ | 526.83$^{abcdefgh}$ | 914.33$^{gh}$ | 74.53$^{abcd}$ |

X1 = pea starch, X2 = feed moisture, X3 = screw speed and X4 = extrusion temperature. − 1 = lowest level of independent variables, 0 = midst level of independent variables and + 1 = highest level of independent variables, Results for each response are the means of multiple determinations of the samples run independently in duplicates

Abbreviations: *ER* expansion ration, *BD* bulk density in grams per cubic centimeter, *WAI* Water Absorption Index, *WSI* Water Solubility Index, *N* Newtons, *N.s* Newton-second, *SME* (kJ/kg) specific mechanical energy in kilojoules per kilogram, *L** lightness, The lowercase superscript alphabet represents the significant difference ($p < 0.05$) between the mean values of each response in the column

The uppercase superscript alphabet A and B in each response column indicates the highest and lowest mean values response variables

Singha & Muthukumarappan, 2018). During extrusion, the pressurized melt exits the die into an environment with much lower atmospheric pressure, causing rapid flash-off of internal moisture. This process generates air pockets within the product, producing the characteristic porous and expanded structure (Altaf et al., 2021; Okunola et al., 2023). Products with higher ER and porosity are generally preferred because they are directly related to the product's degree of starch gelatinization and crispness, as they indicate efficient expansion, uniform air cell distribution, and desirable textural qualities such as crispness and lightness (Lyu et al., 2023; Mohammed et al., 2024; Sharma & Gujral, 2013). Ultimately, the extent of expansion depends on the vapor pressure difference between water in the melt and the surrounding atmosphere, as well as the structural integrity of the extrudate during puffing (Rani et al., 2021; Singh et al., 2014).

The regression equation obtained for ER is represented in Eq. 7.

$$\text{Expansion ratio} = 1.69 + 0.19X_1 - 0.22X_2 - 0.08X_3 - 0.13X_4 + 0.15X_2X_4 - 0.24X_1^2 - 0.18X_4^2 \quad (7)$$

The regression equation (Eq. 7) for ER showed a positive effect of starch ($X_1$) but negative effects of moisture ($X_2$), screw speed ($X_3$), and temperature ($X_4$), with $X_2X_4$ being the only notable positive interaction. The negative quadratic

**Table 5** Analysis of variance (ANOVA) for best-fit models for response

| Source | Sum of squares | Degrees of freedom | Mean square | *F* value | *p* value | Remarks |
|---|---|---|---|---|---|---|
| Expansion ratio | | | | | | |
| Model | 2.02 | 14.00 | 0.14 | 6.33 | 0.00 | Significant |
| Residual | 0.27 | 12.00 | 0.02 | | | |
| Lack of fit | 0.27 | 10.00 | 0.03 | 15.60 | 0.06 | Not significant |
| Pure error | 0.00 | 2.00 | 0.00 | | | |
| Cor Total | 2.30 | 26.00 | | | | |
| Bulk Density | | | | | | |
| Model | 0.0768 | 14 | 0.0055 | 7.25 | 0.0007 | Significant |
| Residual | 0.0091 | 12 | 0.0008 | | | |
| Lack of fit | 0.0088 | 10 | 0.0009 | 6.61 | 0.1385 | Not significant |
| Pure error | 0.0003 | 2 | 0.0001 | | | |
| Total | 0.0859 | 26 | | | | |
| WAI | | | | | | |
| Model | 8.14 | 14 | 0.5815 | 19.74 | < 0.0001 | Significant |
| Residual | 0.3535 | 12 | 0.0295 | | | |
| Lack of fit | 0.3493 | 10 | 0.0349 | 16.64 | 0.058 | Not significant |
| Pure error | 0.0042 | 2 | 0.0021 | | | |
| Cor Total | 8.49 | 26 | | | | |
| WSI | | | | | | |
| Model | 292.85 | 14 | 20.92 | 6.45 | 0.0013 | Significant |
| Residual | 38.91 | 12 | 3.24 | | | |
| Lack of fit | 31.45 | 10 | 3.15 | 0.8437 | 0.6548 | Not significant |
| Pure error | 7.46 | 2 | 3.73 | | | |
| Cor Total | 331.76 | 26 | | | | |
| Hardness | | | | | | |
| Model | 13,049.18 | 14 | 932.08 | 5.24 | 0.0033 | Significant |
| Residual | 2134.11 | 12 | 177.84 | | | |
| Lack of fit | 2109.68 | 10 | 210.97 | 17.27 | 0.0559 | Not significant |
| Pure error | 24.43 | 2 | 12.22 | | | |
| Cor Total | 15,183.29 | 26 | | | | |
| Crispiness | | | | | | |
| Model | 3.27E + 05 | 14 | 23,381.7 | 3.49 | 0.0182 | Significant |
| Residual | 80,451.83 | 12 | 6704.32 | | | |
| Lack of fit | 78,654.4 | 10 | 7865.44 | 8.75 | 0.1068 | Not significant |
| Pure error | 1797.44 | 2 | 898.72 | | | |
| Cor Total | 4.08E + 05 | 26 | | | | |
| SME | | | | | | |
| Model | 5.60E + 05 | 14 | 39,972.07 | 44.4 | < 0.0001 | Significant |
| Residual | 10,802.57 | 12 | 900.21 | | | |
| Lack of fit | 10,532.26 | 10 | 1053.23 | 7.79 | 0.119 | Not significant |
| Pure error | 270.32 | 2 | 135.16 | | | |
| Total | 5.70E + 05 | 26 | | | | |
| Color(L*) | | | | | | |
| Model | 101.64 | 14 | 7.26 | 5.68 | 0.0023 | Significant |
| Residual | 15.34 | 12 | 1.28 | | | |
| Lack of fit | 13.74 | 10 | 1.37 | 1.71 | 0.4241 | Not significant |
| Pure error | 1.6 | 2 | 0.8016 | | | |
| Cor Total | 117.32 | 26 | | | | |

Abbreviations: *ER* expansion ration, *BD* bulk density in grams per cubic centimeter, *WAI* Water Absorption Index, *WSI* Water Solubility Index, *SME (kJ/kg)* specific mechanical energy in kilojoules per kilogram, *L** lightness, *Cor Total* corrected total

**Table 6** Regression coefficient and coefficient of determination for the model

| Variables | ER | BD (g/cm$^3$) | WAI (g/g) | WSI (%) | Hardness (N) | Crispiness (N.s) | SME (KJ/Kg) | Color(L*) |
|---|---|---|---|---|---|---|---|---|
| Intercept | 1.69* | 0.14* | 5.03* | 27.19* | 54.49* | 496.50* | 895.81* | 74.32* |
| $X_1$ | 0.19** | 0.00 | 0.59** | −0.96* | −6.64 | −6.90 | 58.38** | 2.35** |
| $X_2$ | −0.22** | 0.05** | 0.34** | −2.39** | 19.68** | 62.78** | −103.10** | 0.41 |
| $X_3$ | −0.08* | −0.02** | −0.21** | 1.86** | −11.45** | −57.29** | 162.36** | |
| $X_4$ | −0.13** | −0.03** | 0.00 | 0.41 | −14.50** | −95.42** | −66.13** | 0.47 |
| $X_1 X_2$ | | | −0.22** | | −14.07 | | −41.40** | −1.04** |
| $X_1 X_4$ | | −0.03* | | | −14.27 | −91.69** | | |
| $X_2 X_3$ | | −0.03** | | | | | | |
| $X_2 X_4$ | 0.15* | −0.02* | 0.14* | −1.88** | | | 26.80* | |
| $X_1^2$ | −0.24** | 0.03** | 0.51** | −3.08** | | −59.95 | −35.37** | 1.79** |
| $X_2^2$ | | 0.03** | | 1.70** | | | | 0.77 |
| $X_3^2$ | | 0.04** | 0.11* | | | | −24.48** | |
| $X_4^2$ | −0.18** | 0.05** | | 2.46** | | | −24.95** | 1.30** |
| $R^2$ | 0.80 | 0.89 | 0.95 | 0.85 | 0.72 | 0.62 | 0.98 | 0.85 |
| Adjusted $R^2$ | 0.73 | 0.82 | 0.93 | 0.79 | 0.63 | 0.51 | 0.96 | 0.79 |
| Predicted $R^2$ | 0.56 | 0.61 | 0.88 | 0.69 | 0.49 | 0.31 | 0.93 | 0.67 |
| Adeq Precision | 12.47 | 11.55 | 23.55 | 15.47 | 10.15 | 9.23 | 31.26 | 13.45 |

$X_1$ pea starch, $X_2$ feed moisture, $X_3$ screw speed, $X_4$ extrusion temperature, $R^2$ coefficient of determination, *Adeq Precision* adequate precision

Abbreviations: *ER* expansion ration, *BD* bulk density in grams per cubic centimeter, *WAI* Water Absorption Index, *WSI* Water Solubility Index, *N* Newtons, *N·s* Newton-second, *SME (kJ/kg)* specific mechanical energy in kilojoules per kilogram, *L** lightness

Values without an asterisk are not significant $p \geq 0.1$

**Statistical significance at $p < 0.05$

*Statistically significant at $0.05 \leq p < 0.1$

terms $X_1^2$ and $X_4^2$ confirm the presence of curvature, indicating that maximum expansion occurs at intermediate levels of these factors rather than at their extremes.

The ER values of the extrudates varied between 1.08 and 2.16 (Table 4). Pea starch 30%, moisture 21%, screw speed 250 rpm and temperature 120 °C resulted in the minimum expansion ratio whereas the maximum expansion ratio was achieved at pea starch 50%, feed moisture 19%, screw speed 250 rpm and extrusion temperature of 120 °C. Figure 10 shows a clear difference between the control sample (a; image credit: Prince Boakye) and the extruded samples (b and c) produced under optimized conditions. The control sample (a) exhibits dense, dark, compact, and minimally expanded structures. In contrast, samples b and c display well-expanded, puffed structures with increased diameter and a more uniform, porous and bright color. These appearance qualities indicate improved expansion under optimized conditions, consistent with typical RTE snack characteristics.

Similar expansion ratio trends have been reported for a variety of extruded products, including rice chickpea flour blends and rice cowpea composite snacks (Altaf et al., 2021; Okunola et al., 2023), potato starch-based expanded snacks (Calvo-Lopez & Martinez-Bustos, 2017), intermediate wheatgrass products (Boakye et al., 2022), extruded barley ready-to-eat snacks (Chou & Hsu, 2021), corn starch passion fruit pulp snacks (Cortés et al., 2014), cereal-based snacks (Hashemian et al., 2025), lotus rhizome broken rice flour blends (Hussain et al., 2017), and blends of finger millet, sweet potato, and soybean composite flour (Mohammed et al., 2024).

In Fig. 2a, the 3D surface plot demonstrates the interactive effects of pea starch and moisture on the ER. ER increased with pea starch content reaching maximum at a moderate level but slightly declined at a higher level indicating a significant quadratic effect. In contrast, feed moisture negatively affected ER, with higher moisture reducing ER. The surface curvature illustrates the presence of interaction and nonlinear effects. Maximum expansion was observed at moderate starch content and lower moisture levels. Perturbation plots in Fig. 2b and c further indicate a nonlinear effect of pea starch and a slight negative influence of screw speed on ER.

Van Hoan et al. (2010) reported that starch serves as the primary component forming the expanded matrix in extruded blends; the observed increase in starch content corresponded with a higher expansion ratio. Feed moisture, barrel temperature, and screw speed interactively influence the ER of extrudates. An increase in moisture reduced expansion ratio, likely due to decreased melt elasticity and increased

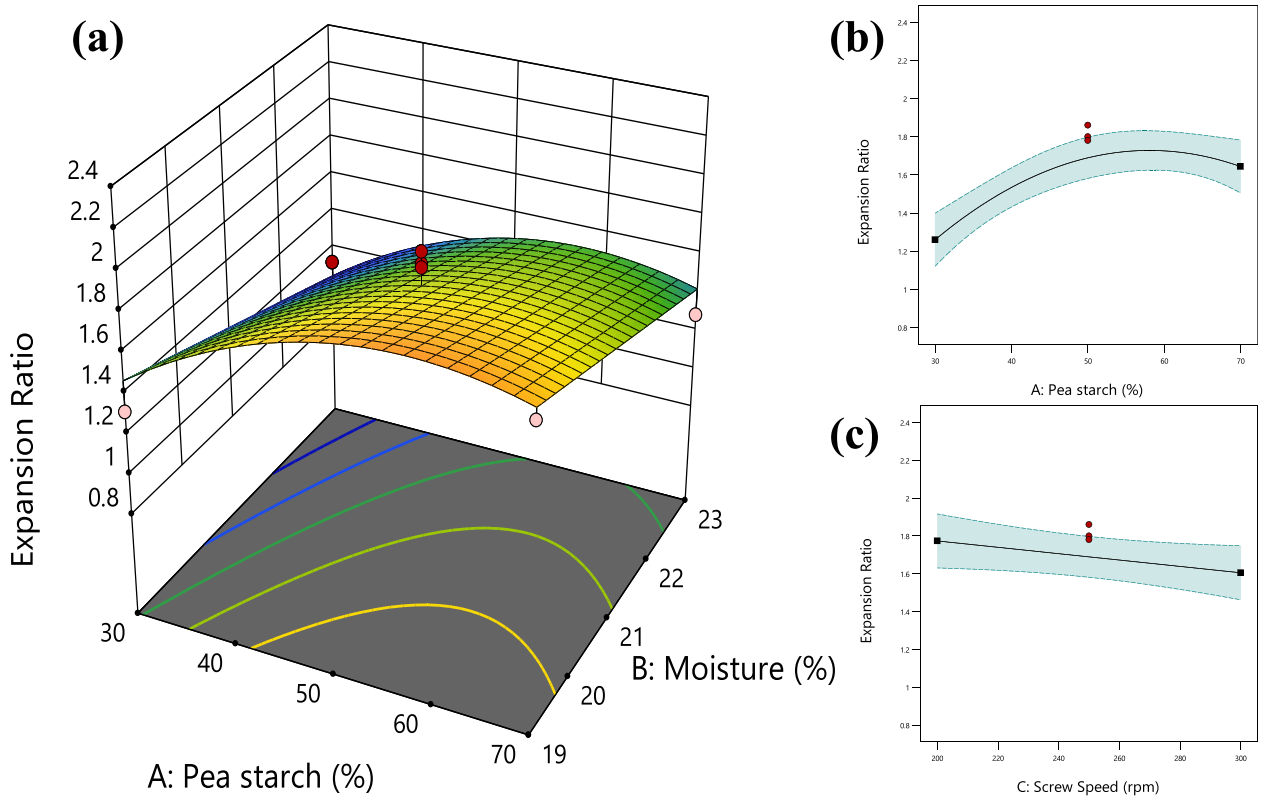



**Fig. 2** **a** Three-dimensional surface shows the combined effect of pea starch and feed moisture on expansion ratio at temperature 135 °C and screw speed 250 rpm based on the fitted regression model. Perturbation plots (**b**, **c**) illustrating the effects of pea starch and screw speed on expansion ratio based on the fitted regression model

plasticity at higher moisture levels (Singh et al., 2015; Srivastava et al., 2012). Barrel temperature generally promoted expansion by increasing steam formation; though excessive heating lowered melt viscosity and risked structural collapse (Calvo-Lopez & Martinez-Bustos, 2017; Gopirajah & Muthukumarappan, 2018). Screw speed effects are temperature dependent, ER increasing at moderate temperature but decreasing at high temperature, reflecting the balance between shear-induced expansion and starch network degradation (Hussain et al., 2017; Rani et al., 2021). Similar interactions among moisture, temperature, and screw speed have been reported for various extruded products (Lyu et al., 2023; Oke et al., 2013).

The ANOVA for the expansion ratio model indicated a significant overall model fit ($p < 0.05$) with an $F$-value of 6.33 (Table 5). The lack-of-fit test was not significant ($p = 0.06$), confirming that the model adequately represented the experimental data. The residual error was minimal, suggesting good precision in the predicted responses.

The fitted model for ER (Table 6) exhibited significant linear effects for all four independent variables, with $X_1$ showing a positive influence ($p < 0.05$) and $X_2$, $X_3$, and $X_4$ exerting negative effects ($p < 0.05$ for $X_2$ and $X_4$; $p < 0.1$ for $X_3$). Among the quadratic terms, $X_1^2$ and $X_4^2$ were significant, indicating curvature in the response, where ER peaked at intermediate levels and declined at the extremes. The interaction between $X_2$ and $X_4$ was the only significant interaction term ($p < 0.1$), suggesting that higher values of both factors slightly increased ER. The model demonstrated a good fit, with $R^2 = 0.80$ and adjusted $R^2 = 0.73$, predicted $R^2 = 0.56$, and an adequate precision of 12.47, exceeding the threshold value of 4.

### Bulk Density (BD)

BD is an important quality characteristic of expanded RTE products and an indicator of expansion, reflecting volumetric puffing in all directions and showing an inverse relationship with the expansion ratio (Delgado-Nieblas et al., 2019; Hussain et al., 2017; Rani et al., 2021). Products with lower BD are lighter, contain more air cells, and are generally more acceptable to consumers, whereas higher BD produces compact, less digestible snacks (Boakye et al., 2022; Mohammed et al., 2024). Beyond consumer perception, BD is also critical for quality control and packaging design, as it influences material requirements, product texture, and mouthfeel (Ali et al., 2024; Okunola et al., 2023).

Equation 8 represented the regression equation obtained for BD.

$$\begin{aligned}\text{Bulk density} &= 0.14 - 0.00X_1 + 0.05X_2 - 0.02X_3 \\ &\quad - 0.03X_1X_4 - 0.03X_2X_3 - 0.02X_2X_4 \\ &\quad + 0.03X_1^2 + 0.03X_2^2 + 0.04X_3^2 + 0.05X_4^2\end{aligned} \quad (8)$$

The regression equation (Eq. 8) for BD indicated a strong positive effect of moisture ($X_2$) and negative effects of screw speed ($X_3$) and temperature ($X_4$). The interaction terms $X_1X_4$, $X_2X_3$, and $X_2X_4$ had negative coefficients, indicating antagonistic effects between variables, where their combined influence leads to a reduction in bulk density. The positive quadratic coefficients ($X_1^2$, $X_2^2$, $X_3^2$, and $X_4^2$) showed curvature in the response. Overall, BD increased with higher moisture but decreased under higher screw speed and temperature, with extreme values of variables leading to denser products.

The BD values of the extrudates ranged between 0.13 and 0.34 g/cm$^3$ (Table 4). Pea starch 50%, moisture 21%, screw speed 250 rpm, and temperature 135 °C yielded extrudates with the lowest bulk density of 0.13 g/cm$^3$ while extrusion parameters pea starch 50%, feed moisture 23%, screw speed 250 rpm, and extrusion temperature of 120 °C produced extrudates of the highest bulk density of 0.34 g/cm$^3$.

Rangira et al. (2020) reported bulk density values ranged from 0.12 to 0.35 g/cm$^3$ in low moisture extrusion of pea starch. Sahu et al. (2022) recorded bulk density values varied from 0.13 to 0.28 g/cm$^3$ the production of soy protein enriched maize-based extruded snack. BD values observed in this study are consistent with previous reports on various extruded products, including lotus rhizome and broken rice flour blends (Hussain et al., 2017), potato starch-based expanded snacks (Calvo-Lopez & Martinez-Bustos, 2017), intermediate wheatgrass extrudates (Boakye et al., 2022), and finger millet sweet potato and soybean composites (Mohammed et al., 2024). Similar findings have also been recorded in cereal-based snacks supplemented with food by-products (Hashemian et al., 2025), rice-cowpea composites (Okunola et al., 2023), kodo millet and chickpea blends (Geetha et al., 2014), rice-chickpea blends, and tigernut-based snacks (Kalahal et al., 2024).

The 3D surface plots in Fig. 3a, b, and c show the interactive effects of process variables on bulk density (BD). BD increased with increasing moisture, while screw speed and temperature showed negative effects, indicating reduced density at higher processing intensities. The curvature of the surfaces confirms the presence of significant quadratic effects, as indicated in the fitted model. Interaction effects, particularly between variables pea starch–temperature and

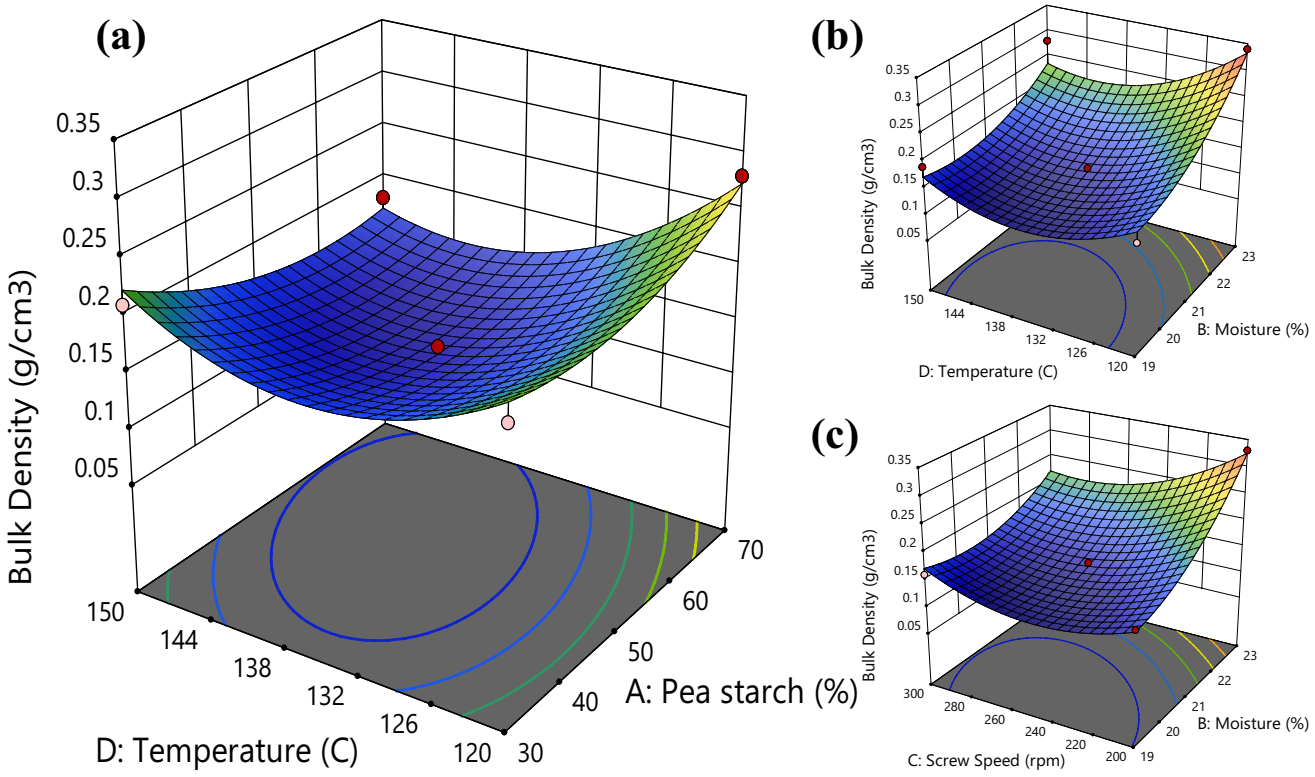



**Fig. 3** Three-dimensional surface plots for bulk density as impacted by different extrusion conditions at **a** moisture 21% and screw speed 250 rpm, **b** pea starch 50% and screw speed 250 rpm, and **c** pea starch 50% and temperature 135 °C based on the fitted regression model

moisture–screw speed, further influenced BD, leading to a nonlinear response. The minimum bulk density was observed at lower moisture and higher screw speed/temperature conditions, suggesting optimal expansion under these processing conditions.

Bulk density (BD) of extrudates is strongly influenced by feed moisture, screw speed, and barrel temperature. Higher feed moisture reduces melt elasticity through plasticization, lowering SME and expansion, and thus increasing BD (Altaf et al., 2021; Chanlat et al., 2011; Hashemian et al., 2025; Mohammed et al., 2024; Singh et al., 2015). In contrast, higher screw speeds lower melt viscosity, improve elasticity, and promote puffing, leading to reduced BD, although excessive shear may degrade starch and limit expansion (Boakye et al., 2022; Hussain et al., 2017; Ye et al., 2018). Barrel temperature also plays a key role, where increased heating enhances starch gelatinization, superheating of water, and flash-off at the die, resulting in larger alveoli, greater expansion, and lower BD (Ali et al., 2024; Geetha et al., 2014; Okunola et al., 2023). However, very high temperatures or high fiber/protein levels may destabilize bubble walls, cause cell collapse, or induce crosslinking, thereby increasing density (Kalahal et al., 2024; Lyu et al., 2023). Overall, BD shows a quadratic response to moisture and temperature, initially decreasing with improved expansion and gelatinization, but increasing at excessive levels due to reduced dough elasticity and structural collapse (Ding et al., 2006; Singha & Muthukumarappan, 2018).

In Table 5, the ANOVA for the bulk density model indicated a significant overall fit ($p < 0.01$; $F = 7.25$), confirming that the selected variables adequately explained the variation in BD. The lack-of-fit test was not significant ($p = 0.14$), suggesting good agreement between predicted and experimental values. The low residual error further supports the reliability and precision of the model.

The fitted model for bulk density (BD) (Table 6) showed a significant positive linear effect of moisture ($X_2$) and negative linear effects of screw speed ($X_3$) and temperature ($X_4$). Interaction effects were negative for $X_1X_4$, $X_2X_3$, and $X_2X_4$ significantly reducing BD. The quadratic terms were positive and significant for all variables, indicating curvature in the response, with BD decreasing at moderate levels but increasing again at higher values. The model explained the variability well ($R^2 = 0.89$; adjusted $R^2 = 0.82$), and the predicted $R^2$ (0.61) indicated moderate predictive accuracy. Adequate precision (11.5) exceeded the threshold value of 4, confirming a strong signal-to-noise ratio and reliability of the model.

### Hardness

Hardness, defined as the maximum force required to fracture an extrudate, is a key quality attribute influencing consumer acceptance (Ali et al., 2024; Charunuch et al., 2014). It is strongly linked with expansion and bulk density, where greater puffing lowers density and hardness, producing lighter and crispier textures (Blandino et al., 2022; Boakye et al., 2022; Calvo-Lopez & Martinez-Bustos, 2017). Lower hardness and breaking strength values are generally preferred, as excessive hardness diminishes crispness and consumer appeal (Altaf et al., 2021; Kalahal et al., 2024).

The regression equation obtained for the hardness of extrudates is represented in Eq. 9.

$$\begin{aligned}\text{Hardness} &= 54.49 - 6.64X_1 + 19.68X_2 \\ &\quad - 11.45X_3 - 14.50X_4 \\ &\quad - 14.07X_1X_2 - 14.27X_1X_4\end{aligned} \tag{9}$$

The regression equation (Eq. 9) for hardness indicates that hardness increased significantly with feed moisture ($X_2$), while pea starch ($X_1$), screw speed ($X_3$), and temperature ($X_4$) exerted strong negative effects, reducing hardness. Several interaction terms ($X_1X_2$ and $X_1X_4$) also showed negative contributions, suggesting that combined increases in these variables lowered hardness further.

The hardness of extrudates varied between 30.33 and 109.74 (N) as represented in Table 4. Pea starch 70%, moisture 21%, screw speed 250 rpm and temperature 150 °C produced extrudates with less hardness while extrusion parameters pea starch 30%, feed moisture 23%, screw speed 250 rpm and extrusion temperature of 135 °C yielded extrudates of more hardness.

In this study, the hardness of extrudates was consistent with reported values (40.07 to 99.96 N) in extrudates from rice-chickpea blends (Altaf et al., 2021). Comparable ranges have also been observed (20.39 to 57.12 N) for expanded intermediate wheatgrass products (Boakye et al., 2022), 23.8–53.3 N in pre-germinated extruded brown rice (Chanlat et al., 2011), and 70.44 to 122.1 N in extruded snacks from finger millet, sweet potato and soybean composites (Mohammed et al., 2024). Similar ranges were noted in rice starch amaranth expanded snacks (Castellanos-Gallo et al., 2019). While higher hardness values (421.1 to 503.0 N) have been documented in whole wheat extrudates (Bhat et al., 2019).

The 3D surface plots in Fig. 4a and b illustrate the interactive effects of process variables on hardness of extrudates. Hardness increased with increasing moisture and decreased with increasing pea starch content, indicating a strong positive effect of moisture and a negative effect of starch. Figure 4b further shows that increasing extrusion temperature reduced hardness, while lower starch levels resulted in higher hardness values. The perturbation plot Fig. 4c indicates a slight negative effect of screw speed on hardness, suggesting that higher shear conditions may weaken product structure. Overall, maximum hardness was observed at higher moisture and lower starch levels, consistent with the fitted regression model.

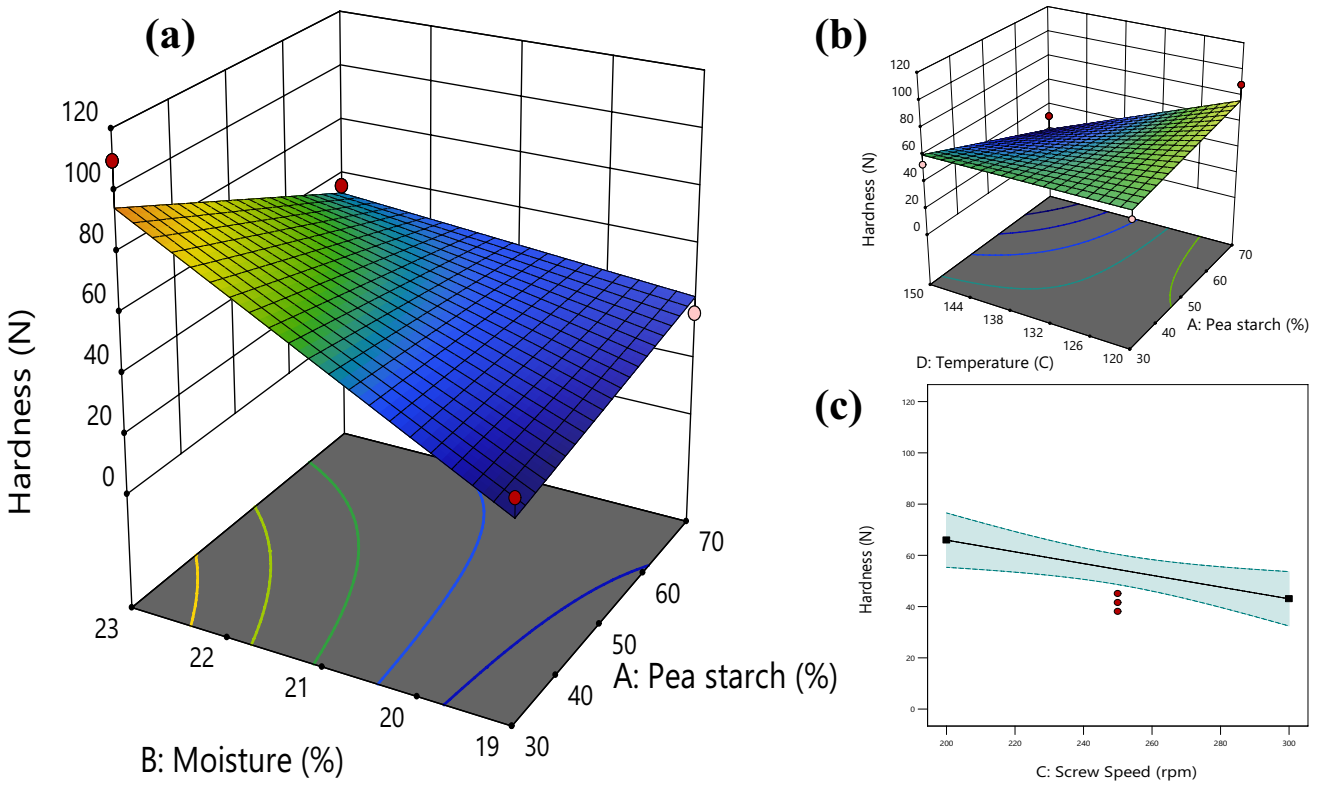



**Fig. 4** Three-dimensional surface plots for hardness as impacted by different extrusion conditions at **a** temperature 135 °C and screw speed 250 rpm, **b** moisture 21% and screw speed 250 rpm, and **c** perturbation plot illustrating the effects of screw speed on hardness based on the fitted regression model

Hardness of extrudates is influenced by screw speed, feed moisture, barrel temperature, starch, and fiber content (Castellanos-Gallo et al., 2019; Kalahal et al., 2024; Mohammed et al., 2024). High feed moisture acted as a plasticizer, reducing dough elasticity and increasing density and hardness (Boakye et al., 2022; Castellanos-Gallo et al., 2019), whereas low moisture promoted dextrinization and fragile cell walls, lowering hardness (Altaf et al., 2021). Increased screw speed and barrel temperature generally reduced hardness by lowering melt viscosity and enhancing bubble growth (Mohammed et al., 2024; Sahu et al., 2022), although excessive shear could toughen textures (Chou & Hsu, 2021). Hardness correlated positively with bulk density and negatively with expansion (Boakye et al., 2022; Chou & Hsu, 2021), while higher fiber levels further increased hardness by limiting starch gelatinization and bubble expansion (Bhat et al., 2019; Bordoloi & Ganguly, 2014).

The ANOVA for hardness in Table 5 confirmed that the model was significant ($p < 0.01$; $F = 5.24$), indicating that the selected variables adequately explained the variation in response. The lack-of-fit was not significant ($p = 0.056$), suggesting good agreement between predicted and experimental values. The relatively low residual error further supports the reliability of the model.

The fitted model for hardness in Table 6 showed a strong positive effect of feed moisture ($X_2$), while pea starch ($X_1$) screw speed ($X_3$) and barrel temperature ($X_4$) had significant negative effects, reducing hardness. The interaction terms ($X_1X_2$, $X_1X_4$) also contributed negatively and were non-significant. The quadratic effects for all variables were not significant. The model explained 72% of the variability ($R^2 = 0.72$; adjusted $R^2 = 0.63$) with an adequate precision of 15.47 and predicted $R^2$ (0.49).

## Crispiness

Crispness, a key texture attribute of RTE snacks, is perceived through a combination of tactile, kinesthetic, visual, and auditory sensations generated by fracture of brittle cellular structures during eating (Ding et al., 2006; Mazumder et al., 2007). It is instrumentally measured by the number of positive peaks in force deformation curves and parameters such as crispness work, puncturing force, and rupture force, which correlate with sensory

perception (Chanlat et al., 2011; Uribe-Wandurraga et al., 2020). Moisture plays an important role, as even small increases in water content reduce crispness and consumer acceptability (Alam et al., 2016; Sahu et al., 2022). Studies confirm that crispness is closely related to extrudate cell structure, with puncture tests and rupture distance effectively quantifying brittleness (Ding et al., 2006).

Equation 10 denotes the regression equation obtained for crispiness of the extrudates.

$$\text{Crispiness} = 496.50 - 6.90X_1 + 62.78X_2 - 57.29X_3 - 95.42X_4 - 91.68X_1X_4 - 59.95X_1^2 \quad (10)$$

The regression equation (Eq. 10) for crispiness showed a strong positive effect of moisture ($X_2$), while screw speed ($X_3$) and barrel temperature ($X_4$) had negative effects, reducing crispiness while pea starch content ($X_1$) showed a minor negative effect. The interaction term $X_1X_4$ had a negative effect, and quadratic terms $X_1^2$ revealed curvature, indicating that extreme levels of variables decreased crispiness, whereas moderate processing conditions favored a lighter, more brittle texture.

The crispiness of the extrudates ranged between 284.68 and 751.43 N·s (Table 4). Pea starch 50%, moisture 21%, screw speed 200 rpm and temperature 120 °C produced extrudates with the highest crispiness while extrusion parameters pea starch 70%, feed moisture 21%, screw speed 250 rpm and extrusion temperature of 150 °C gave extrudates of lowest crispiness.

The 3D surface plot in Fig. 5a illustrates the effects of processing variables on crispiness. The response surface shows that crispiness increased with increasing pea starch content and decreased with increasing temperature, indicating a positive effect of starch and a strong negative effect of temperature. The surface curvature suggests a nonlinear effect of pea starch within the studied range. The perturbation plots in Fig. 5b and c further show that feed moisture positively influenced crispiness, whereas screw speed negatively affected crispiness. Overall, higher crispiness was favored by higher pea starch and moisture levels combined with lower screw speed and temperature.

Crispness of extrudates was strongly affected by extrusion variables, particularly feed moisture, barrel temperature, and screw speed. High barrel temperature enhanced expansion and porosity, resulting in thinner cell walls and more

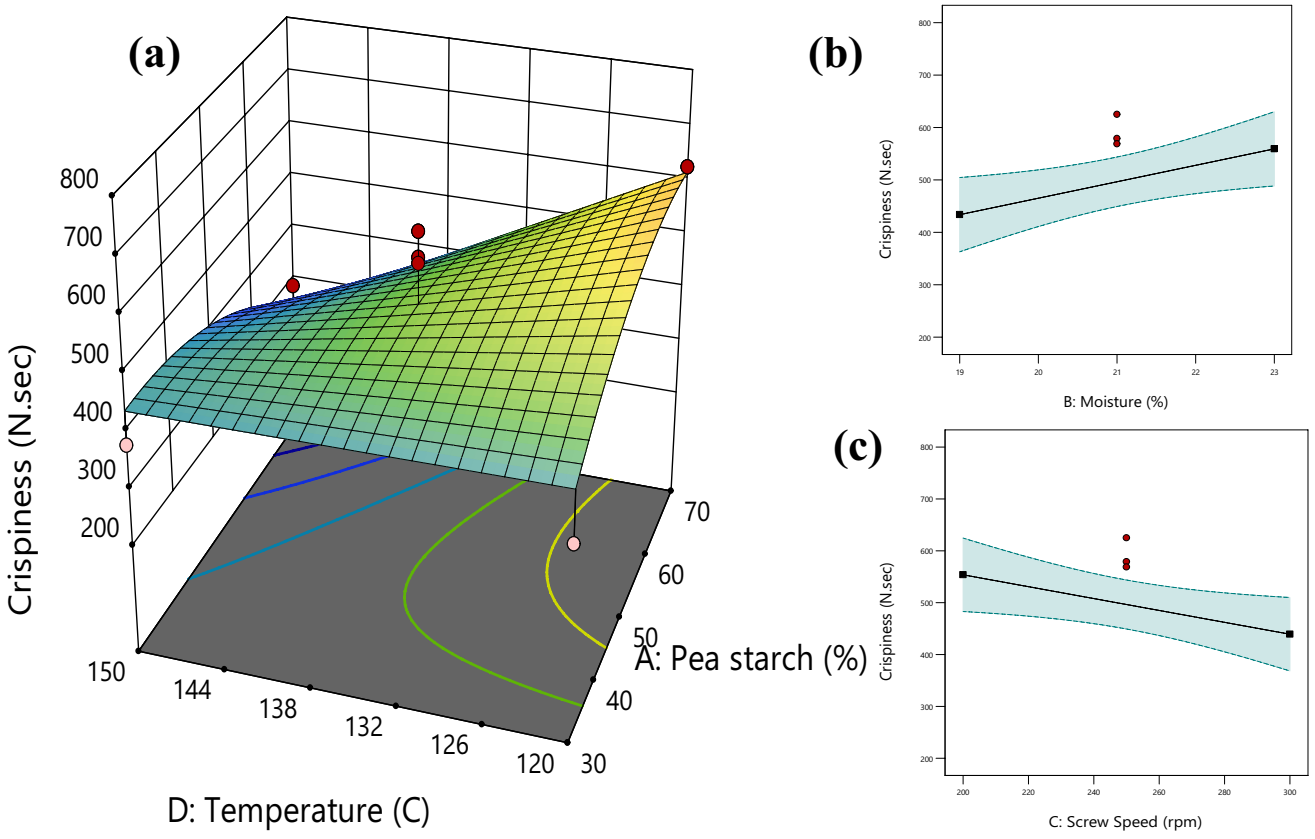



**Fig. 5** Three-dimensional surface plot for crispiness as impacted by different extrusion conditions at **a** moisture 21% and screw speed 250 rpm. **b**, **c** Perturbation plots represent the individual effects of feed moisture and screw speed on crispiness, based on the fitted regression model

brittle textures (Mohammed et al., 2024). Screw speed also improved crispness at elevated temperatures by promoting puffing and bubble formation (Geetha et al., 2014). Excessive dietary fiber and protein limited expansion by restricting starch gelatinization and water mobility, thereby reducing crispness (Beck et al., 2018; Castellanos-Gallo et al., 2019; Félix-Medina et al., 2020).

The ANOVA (Table 5) for crispiness showed that the model was significant ($p < 0.05$; $F = 3.49$), confirming that the process variables had a meaningful effect on crispness. The lack-of-fit was not significant ($p = 0.11$), indicating good agreement between predicted and experimental values. The relatively low residual error further supports the adequacy and reliability of the model.

The fitted model for crispiness (Table 6) indicated a positive effect of feed moisture ($X_2$), while pea starch ($X_1$), screw speed ($X_3$), and barrel temperature ($X_4$) exerted significant negative effects, reducing crispiness. Interaction terms such as $X_1X_4$ were negative and significant while the quadratic term ($X_1^2$) was negative and not significant. The model explained 62% of the variability ($R^2 = 0.62$), though the adjusted $R^2$ (0.51) and predicted $R^2$ (0.31) indicated limited predictive ability beyond the experimental range. Adequate precision (9.23) exceeded the threshold of 4.

## Optical Property of the Extrudates

### Color

Color is an important quality attribute of extruded snacks, directly influencing consumer acceptance and serving as an indicator of the extent of thermal processing (Altaf et al., 2021; Jacques-Fajardo et al., 2017). It is commonly measured using the CIELAB scale (L*, a*, b*), with L* being particularly useful for assessing browning kinetics (Kalahal et al., 2024; Sharma & Gujral, 2013). Color changes during extrusion are mainly attributed to non-enzymatic browning reactions such as Maillard reactions and caramelization, along with pigment oxidation and degradation (Boakye et al., 2023a, 2023b; Pismag et al., 2024; Sukumar & Athmaselvi, 2019). Starch degradation into sugars and their interaction with free amino acids enhances these reactions, while protein and fiber may partially mitigate reductions in lightness (Singha et al., 2018; Zhang et al., 2020). Monitoring color parameters post-extrusion is thus essential to evaluate browning, pigment degradation, and overall product quality (Hashemian et al., 2025).

Equation 11 represents the regression equation obtained for the color of extrudates.

$$\text{Color}(L*) = 74.32 + 2.35X_1 + 0.41X_2 + 0.47X_4 - 1.04X_1X_2 + 1.79X_1^2 + 0.77X_2^2 + 1.30X_4^2 \quad (11)$$

The regression equation (Eq. 11) for color (L*) showed strong positive effects of starch ($X_1$). Feed moisture ($X_2$) and temperature ($X_4$) also exhibited slight positive effects on L*, while negative interaction terms ($X_1X_2$) indicated some combined effects reducing lightness. The quadratic terms ($X_1^2$, $X_2^2$ and $X_4^2$) reflected curvature in the response suggesting color improving at moderate conditions but declining under extremes due to intensified browning reactions.

The L* values of the extrudates ranged between 72.71 and 80.55 (Table 4). In this study, the L* values of extrudates were comparable to ranges reported in previous studies. Ali et al. (2024) observed L* values between 74.08 and 79.79, while tigernut-based snacks showed values of 68.86 to 74.30 (Kalahal et al., 2024). Broader ranges of lightness have been reported, such as 64.69 to 91.25 in extrudates from distiller's dried grains, garbanzo flour, and corn grits (Singha et al., 2018), 68.85 to 89.78 in rice–chickpea blends (Altaf et al., 2021), and 68.58 to 86.95 in corn extrudates with red lentil bran (Kesre & Masatcioglu, 2022). Lower L* values (58.32 to 70.12) were documented in cereal-based snacks enriched with by-products, reflecting higher browning intensity (Hashemian et al., 2025).

Extrusion conditions affected the color and appearance of extrudates. Higher barrel temperatures promoted Maillard and caramelization reactions between sugars and proteins, leading to reduced L* values and darker products (Ali et al., 2024; Altaf et al., 2021; Okunola et al., 2023; Singha et al., 2018). Increased temperature and feed moisture enhanced starch degradation and sugar amino interactions, further contributing to browning and pigment oxidation (Hashemian et al., 2025; Pismag et al., 2024; Zhang et al., 2020). High protein content favored Maillard reactions, while compact air cells at elevated moisture increased light absorption, darkening the extrudates (Altaf et al., 2021). In contrast, higher screw speeds shortened residence time, limiting browning and sometimes increasing the color (Pismag et al., 2024). Pigment degradation, particularly carotenoids, also contributed to the reduction in luminosity at higher temperatures (Kesre & Masatcioglu, 2022).

The ANOVA for color in Table 5 showed that the model was significant ($p < 0.01$; $F = 5.68$), indicating that extrusion variables had a meaningful effect on color attributes. The lack-of-fit test was not significant ($p = 0.42$), confirming good agreement between predicted and experimental values. The relatively low residual error further supports the adequacy and reliability of the model. The surface plots showed that moderate starch, moisture, screw speed, and temperature maintained higher L* values, while extreme conditions reduced lightness. Higher barrel temperature and feed moisture promoted Maillard and caramelization reactions, darkening the extrudates. In contrast, intermediate screw speeds limited browning, helping preserve product luminosity.

For color (L*), the fitted model in Table 6 recorded a significant positive linear effects of starch ($X_1$) while moisture ($X_2$) and temperature ($X_4$) showed positive effect but not significant. Negative interaction effects ($X_1X_2$) suggested that combined increases in starch-moisture reduced L* values, consistent with browning during extrusion. Significant positive quadratic terms ($X_1^2$, $X_4^2$) highlighted curvature, where extreme conditions decreased luminosity due to intensified Maillard and pigment-degradation reactions. The model explained 85% of the variation ($R^2 = 0.85$) adjusted $R^2 = 0.79$, with adequate precision (13.45) confirming model reliability, though the predicted $R^2$ (0.67) indicated only moderate predictive strength.

## Hydrational Properties of Extrudates

### Water Absorption and Water Solubility Indices (WAI and WSI)

The WAI and WSI are key indicators of starch transformation during extrusion, reflecting the degree of gelatinization and degradation. WAI measures the water absorbed and retained as gel after starch swelling, serving as an index of starch digestibility and cooking quality (Alajil et al., 2020; Altaf et al., 2021; Hussain et al., 2017). In contrast, WSI quantifies the soluble polysaccharides released from starch, indicating molecular breakdown and dextrinization (Alam et al., 2016; Ding et al., 2006). Higher extrusion temperatures generally increase WSI by enhancing starch degradation and sugar-amino interactions, while protein and fiber may modulate these effects (Hashemian et al., 2025; Zhang et al., 2020). Low WSI values are desirable for breakfast cereals, which must retain crispness in milk, whereas higher WSI may be beneficial in baby foods requiring rapid solubility (Charunuch et al., 2014; Kowalski et al., 2015). Together, WAI and WSI provide essential insights into the functional properties, texture, and digestibility of extruded snacks (Boakye et al., 2022; Pismag et al., 2024).

The regression equations obtained for water absorption and water solubility indices are represented in Eqs. 12 and 13, respectively.

$$\begin{aligned} WAI &= 5.03 + 0.59X_1 + 0.34X_2 - 0.21X_3 - 0.00X_4 \\ &\quad - 0.22X_1X_2 + 0.14X_2X_4 + 0.51X_1^2 + 0.11X_3^2 \end{aligned} \quad (12)$$

$$\begin{aligned} WSI &= 27.19 - 0.96X_1 - 2.39X_2 + 1.86X_3 + 0.41X_4 \\ &\quad - 1.88X_2X_4 - 3.08X_1^2 + 1.70X_2^2 + 2.54X_4^2 \end{aligned} \quad (13)$$

The regression equation (Eq. 12) for WAI showed that starch ($X_1$) and moisture ($X_2$) had positive effects, while screw speed ($X_3$) reduced water absorption, indicating that higher starch and moisture promoted gelatinization whereas shear limited swelling. The effect of temperature ($X_4$) was negligible. The interaction ($X_1X_2$) was negative while the positive ($X_2X_4$) interaction suggests a synergistic effect between moisture and temperature. The quadratic terms ($X_1^2$, $X_3^2$) highlighted curvature, with WAI increasing under moderate conditions but declining at extremes. On the other hand, the regression equation (Eq. 13) for WSI revealed negative effects of $X_1$ and $X_2$, while $X_3$, and $X_4$ increased solubility, reflecting greater starch degradation under high shear and heat. Interaction ($X_2X_4$) has negative effects while the quadratic terms revealed both negative and positive curvature effects. $X_1^2$ has a negative effect while $X_2^2$ and $X_4^2$ have positive effects further confirmed that WSI rose with intense processing but declined at excessive starch or moisture levels. Together, these models demonstrate that WAI is favored by starch gelatinization under moderate processing, whereas WSI is promoted by molecular breakdown under higher thermal and mechanical inputs.

The values for WAI and WSI of the extrudates ranged between 4.49 to 6.59 g/g and 21.45 to 35.91%, respectively (Table 4). Extrusion conditions of pea starch 30%, moisture 19%, screw speed 250 rpm and temperature 135 °C resulted in minimum WAI, while of pea starch 70%, moisture 21%, screw speed 200 rpm and temperature 135 °C maximized the WAI of extrudates. In contrast, extrusion parameters: pea starch 30%, moisture 23%, screw speed 250 rpm, and temperature 135 °C yielded low WSI, while high WSI was reported under extrusion conditions of pea starch 50%, feed moisture 19%, screw speed 250 rpm, and extrusion temperature of 150 °C.

The WAI and WSI values in this study aligned well with literature ranges for extruded snacks. Reported WAI values include 5.77 to 6.40 g/g for quinoa (Alajil et al., 2020), 2.68 to 7.05 g/g for lotus-rice blends (Hussain et al., 2017), 3.7 to 4.5 g/g for wheatgrass (Boakye et al., 2022), 3.75 to 4.71 g/g for millet-soy blends (Mohammed et al., 2024), and up to 8.17 g/g for rice-chickpea snacks (Altaf et al., 2021). Similar values were also reported for kodo-chickpea (Geetha et al., 2014), by-product fortified snacks (Hashemian et al., 2025), rice-cowpea (Okunola et al., 2023), and soy-maize extrudates (Sahu et al., 2022). WSI values varied from 2.8 to 20% for rice-cowpea (Okunola et al., 2023), 16.65 to 32.75% for by-product fortified snacks (Hashemian et al., 2025), 12.59 to 20.93% for quinoa (Alajil et al., 2020), 15.91 to 30.98% for intermediate wheatgrass extrudates (Boakye et al., 2023a, 2023b), and 9.05 to 18.87% for rice-chickpea blends (Altaf et al., 2021). Overall, WAI reflected starch gelatinization, while WSI indicated starch degradation, both strongly influenced by extrusion conditions and formulation.

Response surface plots in Fig. 6a and b for WAI and in Fig. 7a. The response surface indicates that WAI increased with increasing feed moisture and pea starch content,

demonstrating a strong positive effect of both variables on water absorption capacity. The surface curvature suggests a nonlinear response, particularly at higher levels of moisture and starch, while the interaction between temperature and moisture shows that WAI increased with moisture, while temperature had a comparatively minor effect, with only slight variation across the studied range. This indicates that moisture was the dominant factor influencing WAI. In Fig. 6c, the perturbation plot reveals that screw speed had a negative effect on WAI, where increasing screw speed reduced water absorption, likely due to increased shear and disruption of the starch matrix. In Fig. 7a, the response surface plot shows that WSI increased with increasing temperature and decreased with increasing moisture, indicating a positive effect of temperature and a negative effect of moisture on WSI. The surface curvature suggests nonlinear behavior, particularly at higher temperature levels. The perturbation plots in Fig. 7b and c further indicate that pea starch content negatively influenced WSI, whereas screw speed had a positive effect, likely due to enhanced molecular breakdown under higher shear conditions. Overall, a higher WSI was observed at higher temperature and screw speed, combined with lower moisture and starch levels.

The WAI and WSI were influenced by extrusion conditions, feed moisture, screw speed, and barrel temperature. WAI generally increased with higher feed moisture due to reduced melt viscosity and enhanced starch gelatinization, though excessive temperature or dextrinization reduced WAI by degrading starch polymers (Hussain et al., 2017; Mohammed et al., 2024; Sahu et al., 2022). Screw speed had mixed effects; lower shear preserved intact polymer chains and hydrophilic groups, increasing WAI, whereas higher speeds induced degradation, lowering absorption capacity (Okunola et al., 2023). In contrast, WSI rose with screw speed and temperature due to starch breakdown into smaller, soluble molecules under high shear and thermal energy, consistent with increased SME and amylopectin depolymerization (Boakye et al., 2022; Ding et al., 2006; Singha et al., 2018). High moisture often decreased WSI, as water plasticized the melt, reduced shear, and limited starch degradation, whereas low moisture enhanced solubility via greater macromolecular damage (Ali et al., 2024; Neder-Suárez et al., 2020).

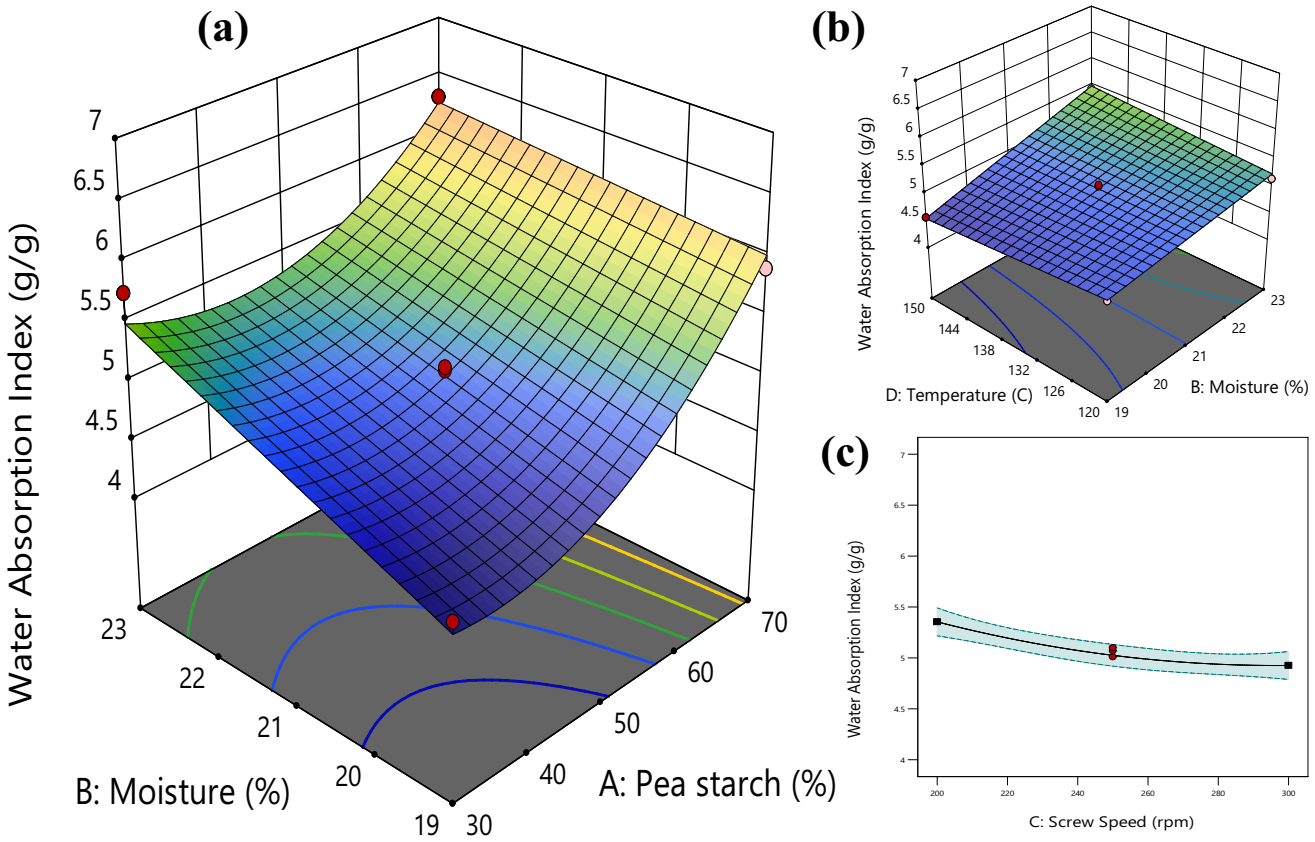



**Fig. 6** Three-dimensional surface plots for water absorption index as impacted by different extrusion conditions at **a** temperature 135 °C and screw speed 250 rpm, **b** pea starch 50% and screw speed 250 rpm, and **c** perturbation plot represents the individual effects of feed moisture and screw speed on water absorption index based on the fitted regression model

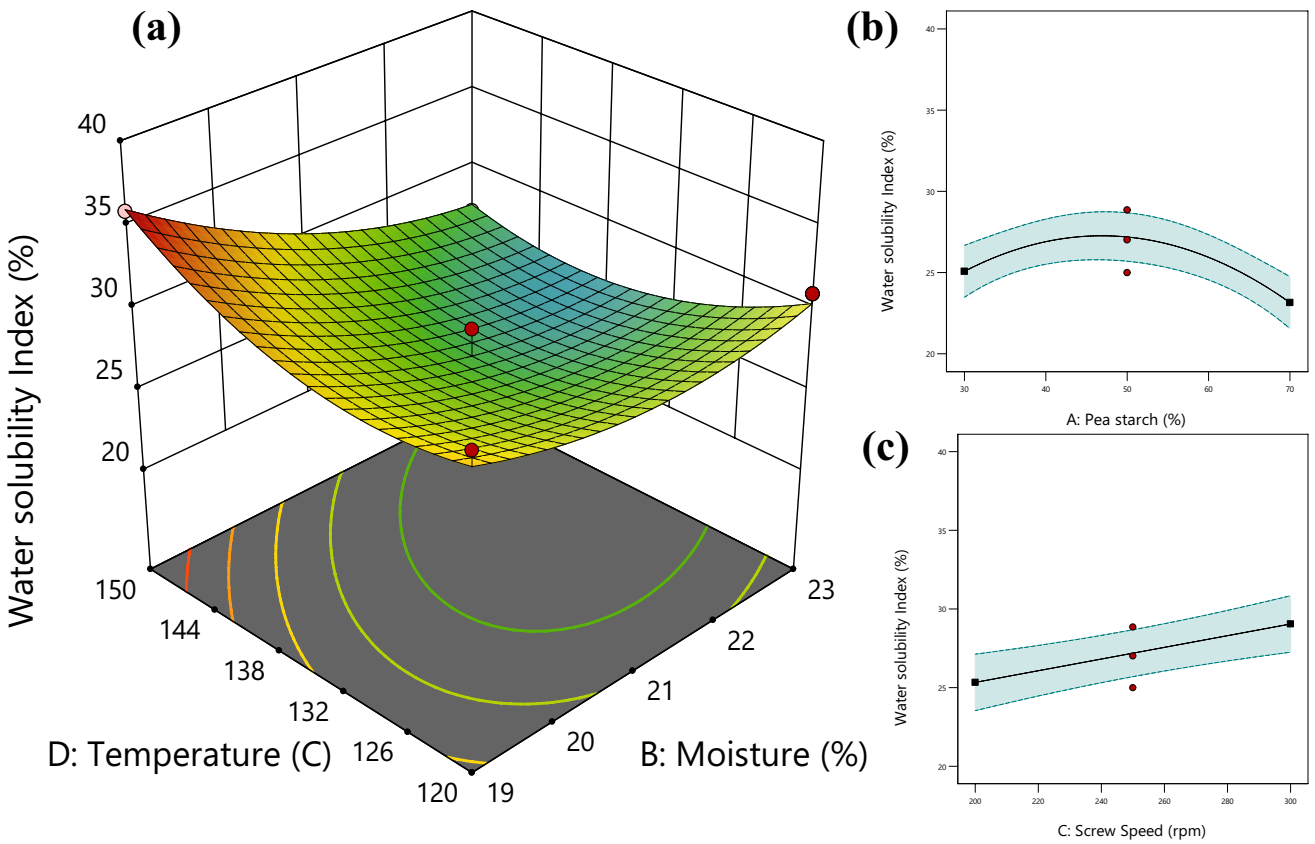



**Fig. 7** Three-dimensional surface plot for water solubility index as impacted by different extrusion conditions at **a** pea starch 50% and screw speed 250 rpm. **b**, **c** Perturbation plots represent the individual effects of pea starch and screw speed on water solubility index based on the fitted regression model

The ANOVA results in Table 5 indicated that the fitted models for both WAI and WSI were highly significant ($p < 0.001$), with $F$-values of 19.74 and 6.45, respectively, confirming the strong influence of extrusion variables. The lack-of-fit tests were not significant for either WAI ($p = 0.058$) or WSI ($p = 0.655$), suggesting that the models adequately described the data. These results validate the predictive capability of the quadratic models, showing that WAI was more strongly explained by process variables compared to WSI, as reflected by its higher model $F$-value.

The fitted model for WAI in Table 6 showed a strong fit ($R^2 = 0.95$, Adj $R^2 = 0.93$, Pred $R^2 = 0.88$), with $X_1$ and $X_2$ exerting significant positive effects, while $X_3$ had a negative impact. Quadratic terms ($X_1^2$, $X_3^2$) further highlighted curvature, indicating that excessive starch or screw speed reduced WAI after reaching optimum levels. The high Adeq Precision (23.55) confirmed excellent signal-to-noise ratio, validating model reliability.

The fitted model for WSI (Table 6), the model was also significant ($R^2 = 0.85$, Adj $R^2 = 0.79$, Pred $R^2 = 0.49$), $X_1$ and $X_2$ showed negative effects and were significantly reducing solubility, while $X_3$ and $X_4$ increased it, reflecting starch degradation under high shear and heat. Interaction effects ($X_2X_4$) were also important, showing that combined variable changes influenced solubility. Quadratic term ($X_1^2$) was negatively significant while ($X_2^2$, $X_4^2$) were positively significant. Adeq Precision (10.15) indicated a sufficiently strong signal, making the model acceptable.

## Processing Response

### Specific Mechanical Energy (SME)

SME, defined as the energy transferred from the motor per unit mass of extruded material, is a key extrusion parameter influencing extrusion efficiency, starch gelatinization, structural transformation, and product expansion (Hussain et al., 2017; Lyu et al., 2023; Rangira et al., 2020). Higher SME enhances starch conversion and expansion by increasing shear and reducing melt viscosity, though excessive inputs may cause macromolecular breakdown and alter viscoelastic properties (Ding et al., 2006; Jebalia et al., 2019; Pietsch et al., 2019). As it reflects screw speed, feed rate, torque, and viscosity, SME is widely used to optimize extrusion conditions and predict

product quality (Beck et al., 2018; Lyu et al., 2023; Philipp et al., 2017).

Equation 14 represented the regression equation obtained for the specific mechanical energy of the extrusion processing.

$$SME = 895.81 + 58.38X_1 - 103.10X_2 + 162.36X_3 - 66.13X_4 - 41.40X_1X_2 + 26.80X_2X_4 - 35.37X_1^2 - 24.48X_3^2 - 24.95X_4^2 \quad (14)$$

The regression equation (Eq. 14) for SME showed that screw speed ($X_3$) exhibited the strongest positive effect, indicating that increasing screw speed significantly increases energy input. Pea starch also showed a positive contribution. In contrast, feed moisture ($X_2$) and extrusion temperature ($X_4$) had negative effects, suggesting that higher moisture and temperature reduce SME, likely due to decreased melt viscosity and resistance to flow. Interaction terms such as $X_1X_2$ have a negative and $X_2X_4$ has a positive effect while quadratic effects ($X_1^2$, $X_3^2$, $X_4^2$) indicated nonlinear responses. The predicted SME values ranged around 895.81 kJ/kg under optimized extrusion conditions.

The SME was reported in the range of 586.40 to 1132.09 kJ/Kg (Table 4). Extrusion conditions pea starch 30%, moisture 21%, screw speed 200 rpm and temperature 135 °C resulted in lower SME while extrusion parameters pea starch 50%, feed moisture 19%, screw speed 300 rpm and extrusion temperature of 135 °C caused higher SME.

SME values reported in extrusion studies vary widely depending on material and conditions. For instance, ranges of 147.89 to 320.22 kJ/kg were observed in lotus rhizome rice blends (Hussain et al., 2017), 213.98 to 539.35 kJ/kg in blue corn, pea, and oat bran extrudates (Jacques-Fajardo et al., 2017), and 64.38 to 138.71 kJ/kg in extrudates from pea starch (Rangira et al., 2020). Higher SME values (100 to 2000 kJ/kg and 503 to 1276 kJ/kg) were reported in pea protein and starch composites respectively (Chen et al., 2021; Jebalia et al., 2019, 2022), while Boakye et al. (2023a, 2023b) found 352.84 to 491.53 kJ/kg in intermediate wheatgrass extrudates. Similarly, Beck et al. (2018) reported SME of 558 kJ/kg for pea protein fiber and rice starch blends.

The response surface plots in Fig. 8a and b illustrated how SME responds to changes in extrusion process variables. SME increased with increasing pea starch and decreased with increasing moisture, indicating that higher starch levels increased energy input, whereas moisture reduced it.

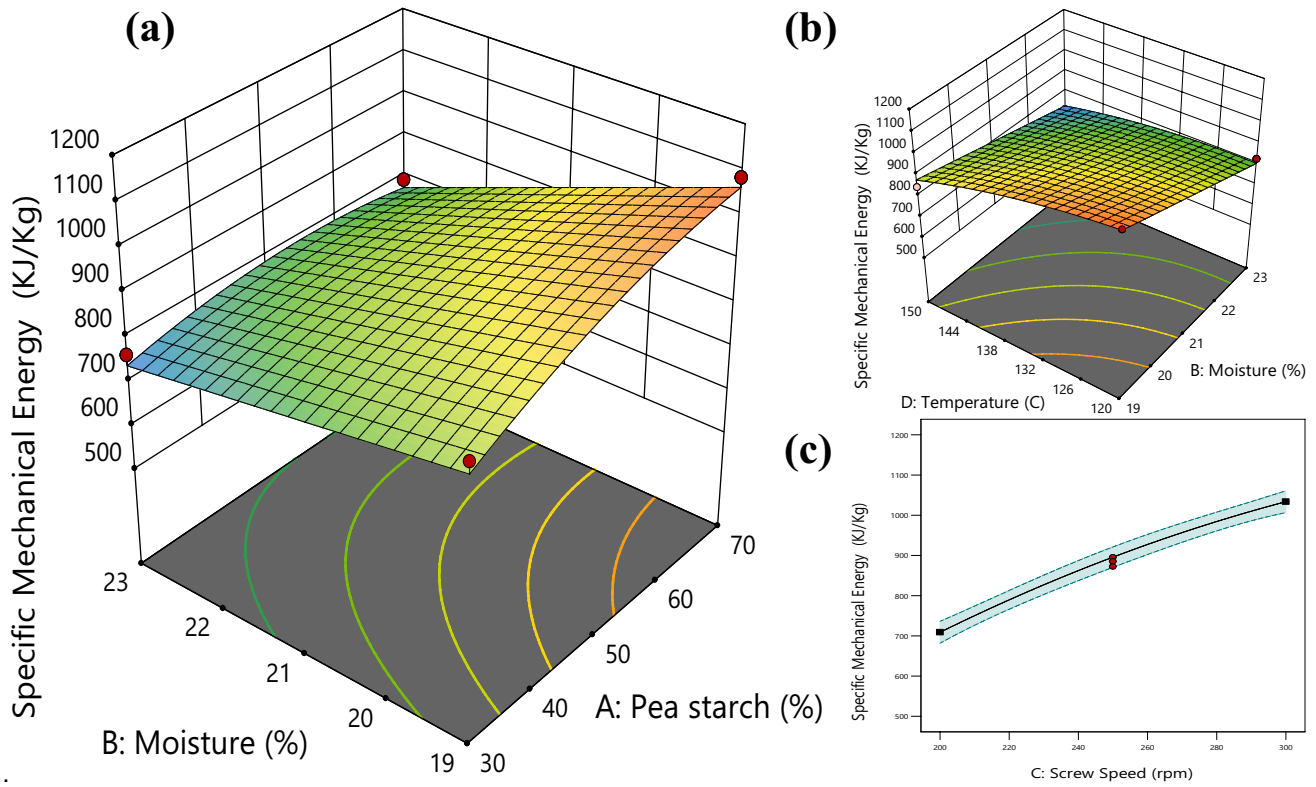



**Fig. 8** Three-dimensional surface plots for specific mechanical energy as impacted by different extrusion conditions at **a** temperature 135 °C and screw speed 250 rpm, **b** pea starch 50% screw speed 250 rpm, **c** perturbation plot shows the individual effect of screw speed on specific mechanical energy based on the fitted regression model

**Table 7** Individual response optimization of the model

| Response variables | Optimum parameters | | | | | |
|---|---|---|---|---|---|---|
| | Pea starch (%) | Moisture (%) | Screw speed (rpm) | Temperature (℃) | Predicted values | Desirability |
| ER | 63.01 | 19.00 | 217.56 | 122.68 | 2.22 (2.53) | 0.99 |
| BD (g/cm$^3$) | 50.00 | 21.00 | 250.00 | 135.00 | 0.14 (0.18) | 0.89 |
| WAI (g/g) | 50.00 | 21.00 | 250.00 | 135.00 | 5.06 (5.28) | 1.00 |
| WSI (%) | 50.00 | 21.00 | 250.00 | 135.00 | 26.95 (29.22) | 1.00 |
| Hardness (N) | 30.00 | 19.00 | 300.00 | 123.19 | 34.8 (43.38) | 1.00 |
| Crispiness (N.s) | 49.81 | 22.57 | 200.00 | 120.00 | 705.47 (880.63) | 0.86 |
| SME (kJ/kg) | 50.00 | 21.00 | 250.00 | 135.00 | 884.13 (921.87) | 1.00 |
| Color (L*) | 50.00 | 21.00 | 250.00 | 135.00 | 74.05 (5.47) | 1.00 |

Abbreviations: *ER* expansion ration, *BD* bulk density in grams per cubic centimeter, *WAI* Water Absorption Index, *WSI* Water Solubility Index, *N* Newtons, *N·s* Newton-second, *SME (kJ/kg)* specific mechanical energy in kilojoules per kilogram, *L** lightness

Data in parenthesis indicated the upper predicated values

The interaction between temperature and moisture further showed a decreasing trend in SME with increasing processing intensity, with moisture having a stronger effect. The perturbation plot in Fig. 8c confirmed that screw speed had a strong positive influence on SME, with higher screw speed increasing energy input through enhanced shear.

SME was influenced by extrusion variables; higher feed moisture and temperature generally reduce SME due to their plasticizing and lubricating effects, which lower dough viscosity and torque requirements (Hussain et al., 2017; Rangira et al., 2020). Conversely, increasing screw speed raises SME by generating higher shear stress and mechanical energy transfer (Boakye et al., 2023a, 2023b; Lyu et al., 2023; Zahari et al., 2023). Elevated SME is often associated with greater starch gelatinization, structural transformation, and improved expansion of extrudates (Okunola et al., 2023; Philipp et al., 2017). However, excessive SME may induce molecular degradation, lowering melt viscosity (Jebalia et al., 2019). Interactions among process variables indicate that high SME values typically occur at low moisture, low barrel temperature, and high screw speed—conditions that maximize shear stress within the barrel (Heredia-Olea et al., 2020; Kesre & Masatcioglu, 2022).

**Table 8** Optimum parameters and predicted values individual response at optimized conditions

| Optimum parameters | Actual values | Desirability |
|---|---|---|
| Pea starch (%) | 54.34 | 1.00 |
| Moisture (%) | 19.57 | 1.00 |
| Screw speed (rpm) | 240.79 | 1.00 |
| Temperature (℃) | 131.42 | 1.00 |
| Response variables | Predicted values | Overall desirability |
| ER | 2.05 | 0.73 |
| BD (g/cm$^3$) | 0.13 | |
| WAI (g/g) | 5.07 | |
| WSI (%) | 28.43 | |
| Hardness (N) | 36.91 | |
| Crispiness (N.s) | 556.30 | |
| SME (KJ/Kg) | 970.69 | |
| Color (L*) | 74.84 | |

Abbreviations: *ER* expansion ration, *BD* bulk density in grams per cubic centimeter, *WAI* Water Absorption Index, *WSI* Water Solubility Index, *N* Newtons, *N·sec* Newton-second, *SME (kJ/kg)* specific mechanical energy in kilojoules per kilogram, *L** lightness

The ANOVA results in Table 5 for SME showed that the quadratic model was highly significant ($p < 0.0001$), with an $F$-value of 44.4, indicating that extrusion variables strongly influenced SME. The lack-of-fit was not significant ($p = 0.119$), confirming that the model adequately represented the data. This suggests that the developed regression model reliably explained the variation in SME across different processing conditions.

The fitted model for SME in Table 6 showed that feed moisture ($X_2$) and extrusion temperature ($X_4$) had significant negative effects, meaning higher levels of these factors reduced SME. In contrast, pea starch ($X_1$) and screw speed ($X_3$) had the strongest positive effect, confirming that higher screw speeds increase SME due to greater shear input. Interaction terms such as $X_1X_2$ were negatively significant, while $X_2X_4$ was positive significant. Among quadratic terms, $X_1^{2,}X_3 2$, and $X_4 2$ showed negative influences, suggesting diminishing effects at extreme levels. For specific mechanical energy (SME), the regression model ($R2 = 0.98$, Adjusted $R2 = 0.96$, Predicted $R2 = 0.93$, Adeq Precision = 31.26) showed an excellent fit, indicating strong predictive reliability.

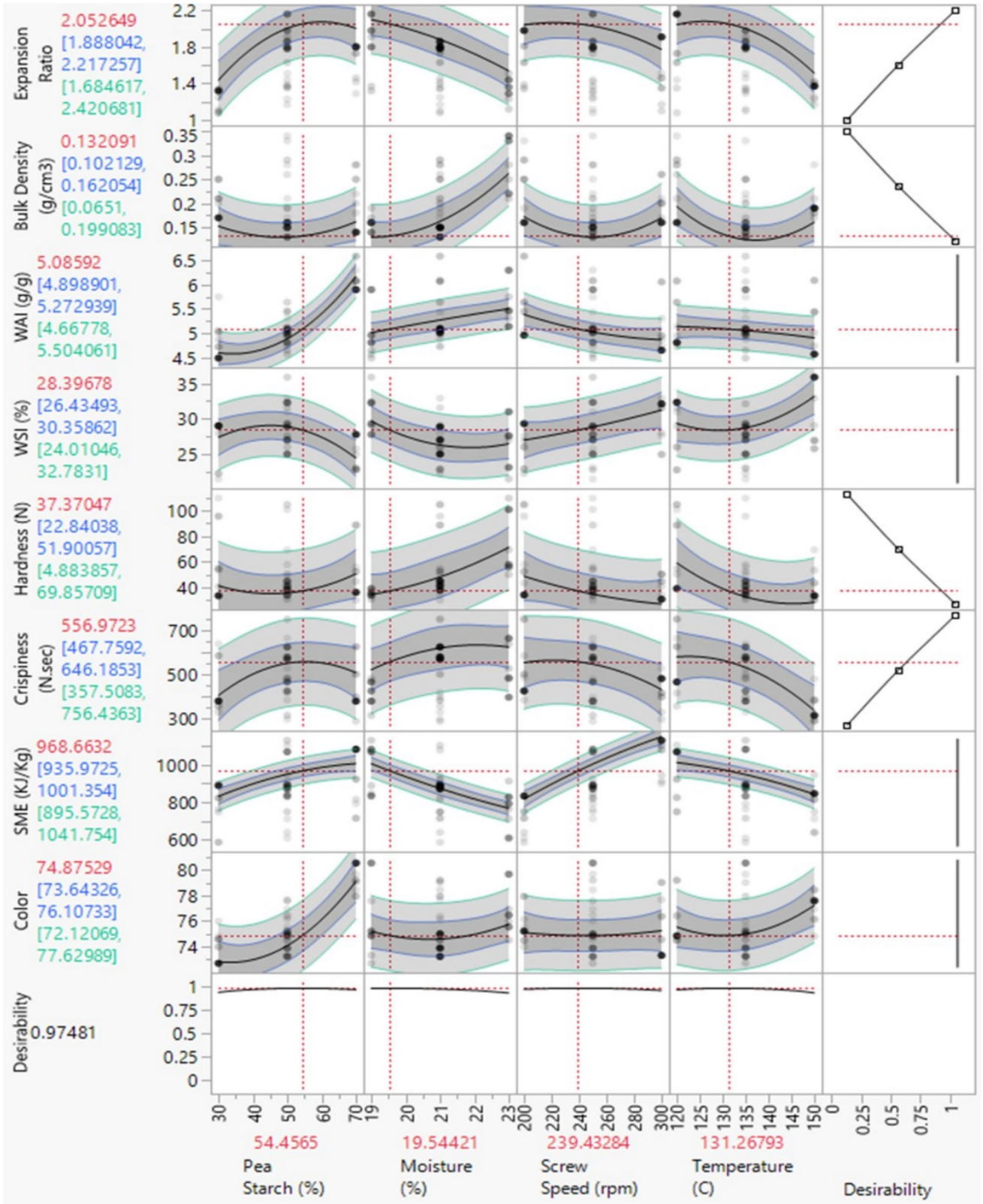



**Fig. 9** Predictions profiler of the optimized region for the extrusion processing parameters pea starch 54.33% and moisture 19.57%, moisture 19.57%, screw speed 240.74 rpm and temperature 131.41 °C for producing extruded product and predicted values of the response variables overall desirability

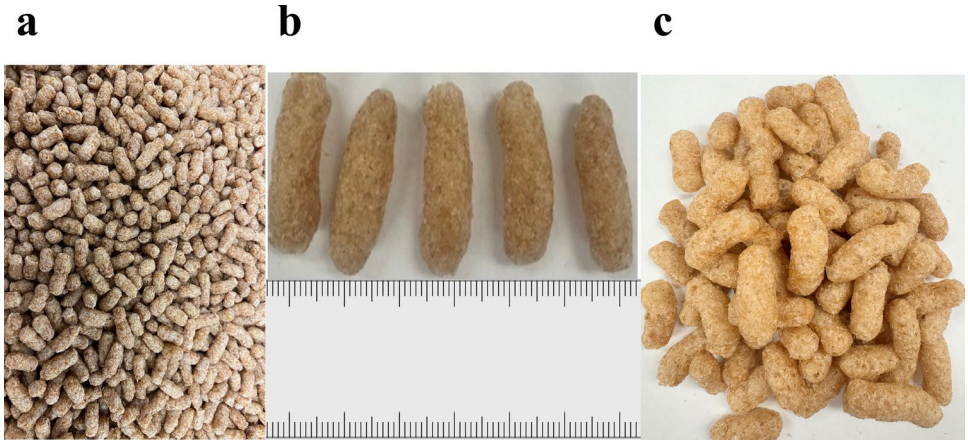



**Fig. 10** Visual comparison of the control sample (**a**; image credit: Prince Boakye) and extruded products obtained under optimized conditions (**b**, **c**). The control exhibits a dense and minimally expanded structure, whereas samples b and c show well-expanded, puffed morphologies characteristic of ready-to-eat snacks

## Optimization

The optimum conditions for each individual response and their predicted values along with desirability are given in Table 7, while the overall optimization of the extrusion processing for RTE snacks with optimized responses (high expansion, low bulk density, lower hardness, and more crispiness) are presented in Table 8. Design-Expert R © software was used for multi-response optimization. JMP software student version 18 was used for graphical presentation of the optimized data (Fig. 9). At the optimized extrusion conditions of 54.34% pea starch, 19.57% feed moisture, 240.79 rpm screw speed, and 131.42 °C barrel temperature, the model predicted desirable product characteristics with high overall desirability of 0.73. The expansion ratio (2.05) and low bulk density (0.13 g/cm$^3$) indicated good puffing, while the WAI (5.07 g/g) and WSI (28.43%) reflected favorable hydration and starch conversion properties. The extrudates were expected to exhibit hardness (36.91 N) and high crispiness (556.30 N·sec), suggesting brittle texture suitable for snack products. A relatively high SME (970.69 kJ/kg) was associated with enhanced starch transformation under these conditions. The lightness of color (L* = 74.84). The overall optimization achieved a balance of structural, textural, and functional attributes appropriate for ready-to-eat extrudates (Fig. 10).

## Conclusion

This research experiment aimed to optimize extrusion conditions for the development of expanded intermediate wheatgrass (IWG) snacks by varying pea starch level, feed moisture, screw speed, and barrel temperature with application of response surface methodology (RSM). The results showed that all variables influenced the physical, texture, and hydration properties of the extrudates. Expansion ratio improved with higher starch and screw speed, whereas increased feed moisture promoted compact structures and higher bulk density. Hydration indices (WAI and WSI) reflected starch gelatinization and degradation, with screw speed and temperature enhancing solubility. Hardness and crispness were strongly linked to expansion and density, while SME served as a key indicator of starch conversion and product quality. Color changes, mainly reductions in L* values, were attributed to Maillard browning and pigment degradation at higher temperature and moisture. The optimum conditions (54.34% pea starch, 19.57% feed moisture, 240.79 rpm screw speed, and 131.42 °C barrel temperature) produced extrudates with desirable functional and sensory properties. The study establishes the potential of IWG as a sustainable raw material for expanded ready-to-eat snacks and cereals, providing insights for both small- and large-scale food industries to design nutrient-rich products with improved consumer acceptability. The results provide a framework for upscaling the extrusion parameters for producing IWG-based puffed products, supporting both nutritional innovation and sustainability in cereal processing. This article demonstrates the feasibility of incorporating an IWG-pea starch blend into puffed RTE snacks by optimizing key extrusion variables. The results indicate that an IWG-pea starch blend yields desirable expansion, texture, and hydration properties. Compared with 100% IWG extrudates, IWG-pea starch-based extrudates exhibited comparable ER, BD, hardness, and crispness, confirming their potential as nutritionally enriched and sustainable snack alternatives.

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**Data Availability** The data generated and analyzed during the current study are available from the corresponding author upon reasonable request.

## Declarations

**Competing interests** The authors declare no competing interests.

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