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Extrusion processing of unripe banana and defatted peanut flours: Effect of process variables on physical and machine parameters

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Abstract
The study aimed to develop nutritionally enriched extruded products using unripe banana flour (UBF) and defatted peanut flour (DPF) through optimization of extrusion parameters. UBF, rich in resistant starch and bioactive compounds and DPF, high in protein and low in fat, were selected as base materials. A Central Composite Rotatable Design (CCRD) under Response Surface Methodology (RSM) was employed to examine the effects of feed moisture content (12-18%), screw speed (200-300 rpm) and die head temperature (90-150 °C) on machine responses (torque, mass flow rate) and physical properties (bulk density, specific length, expansion ratio). Experimental results showed that torque ranged from 15-23 Nm, mass flow rate from 135-170 g/min, bulk density from 0.043-0.066 g/cm³, specific length from 91.11-171.95 mm/g and expansion ratio from 2.13-3.29. Feed moisture, screw speed and die head temperature significantly influenced these responses, with higher screw speed and lower moisture enhancing flow rate, elongation and expansion while reducing bulk density. Regression models were significant (R^2 = 0.84-0.99) with non-significant lack of fit, confirming model adequacy. Optimization suggested ideal conditions at 13.21% feed moisture, 270 rpm screw speed and 117 °C die head temperature. Validation under these conditions showed close agreement between predicted and experimental values with minimal deviations: torque (16.30 Nm), mass flow rate (162.01 g/min), bulk density (0.040 g/cm³), specific length (175.32 mm/g) and expansion ratio (3.01). The findings demonstrate that UBF-DPF blends can be effectively processed into extruded snacks with desirable physical qualities, enabling value-added utilization of underutilized resources and supporting the development of protein-and fiber-rich ready-to-eat products.

Keywords: Unripe banana flour, defatted peanut flour, extrusion cooking, response surface methodology, optimization, ready-to-eat snacks

Introduction

Banana is the common name of herbaceous plants of the genus *Musa*. Banana plants are monocotyledons, perennial and important crops in the tropical and subtropical world region (Strosse *et al.*, 2006) [38]. In terms of gross value of production, bananas (*Musa* spp.) are the developing world's fourth most important crop after rice, wheat and corn (Olaoye *et al.*, 2011) [32]. Banana is a major enterprise in India, generating about ₹587.16 billion and supporting millions of farmers. India contributes 27% of global banana production, with 31.74 million tons grown on 8.98 lakh ha (Uma and Kumar, 2020) [40]. Post-harvest losses in banana amount to about 15.43%, including 0.77% in the field, 5.86% during transport and 8.80% during ripening (Davara and Patel, 2011) [10]. Unripe banana flour (UBF) is nutritionally rich in carbohydrates, protein, vitamins and minerals, with high water absorption and low gluten. It is used in baby foods, bakery products and as a wheat substitute (Akubor, 1998; Mepba *et al.*, 2007) [1, 27].

Peanut is a major oilseed crop of India. However, unlike other oilseeds, groundnut can be consumed directly as food. They have a rich nutty flavour, sweet taste, crunchy texture and over and above a relatively longer shelf life (Vora *et al.*, 2025) [41]. With the growing awareness among people about the importance of balanced diet, demand for low-calorie high protein foods is increasing as people tend to avoid consumption of high-fat foods lest it should cause obesity and associated health problems (Blundell and Macdiarmid, 1997) [8].

The peanut is a main crop in Saurashtra region of Gujarat, where it is one of the most affordable protein sources. Peanuts are crucial as an oil-bearing seed globally, rapidly becoming a valuable plant protein source. The seeds provide protein, lipids and fatty acids essential for human nutrition (Tai and Young, 1975; Gaydou *et al*., 1983; Kumar *et al*., 2025) [39, 18, 24]. The utilization of defatted peanut meal in food products offers a promising approach to increase groundnut protein consumption. It can be incorporated as a low-fat groundnut concentrate, composite flour, or functional ingredient in various food items such as bakery products, breakfast cereal flakes, snack foods, multipurpose supplements, infant and weaning foods and extruded meals (Vyas *et al*., 2023) [42]. Peanuts rank fifth globally in vegetable oil production, with the by product, peanut oil cake or meal, used post-oil extraction (Kain *et al*., 2009) [21]. Processed into partially defatted peanut flour (DPF), it retains protein richness (47-55%) and essential amino acids, making it ideal for diverse food applications (Kain *et al*., 2009; Rehrah *et al*., 2009; Ma *et al*., 2010) [21, 33, 25]. The nutritive value of any peanut product is closely associated with the fatty acid composition of its oil content, which influences its quality (Dhamsaniya *et al*., 2012) [14].

Extrusion cooking, similar to thermoplastic processing, is favored for producing food analogues from cereals and legumes (Moscicki and Zuilichem, 2011) [30]. It efficiently texturizes proteins and is cost-effective for high-volume food processing (Chocha *et al*., 2024) [9]. The history of extrusion in food processing dates back to the 1930's with the introduction of the "forming extruder," a fundamental design used for manufacturing pasta products. Over time, as various types of extruders evolved, extrusion technology became integral to the food industry, contributing to the development of diverse products such as precooked and modified starches, Ready-To-Eat (RTE) cereals, snack foods, Texturized Vegetable Proteins (TVP), breading substitutes and more (Harper and Clark, 1979) [20]. Extrudates are one of the major growing commodities in snack foods (Gojiya *et al*., 2022) [19]. Continuous improvements in these foundational products continue to cater to the evolving preferences and needs of consumers. The extrusion process involves the continuous processing of food, incorporating unit operations like mixing, kneading and shaping dough. It has been widely adopted as a popular approach for producing a wide range of food products, from basic enlarged snacks to highly processed meat substitutes. (Sapariya *et al*., 2022) [34]. For instance, extruded snack products have been prepared by blending corn flour with defatted peanut flour using a twin-screw extruder (Davara *et al*., 2022) [11].

Materials and Methods

Raw Material

The important ingredients used in the development of extruded products were unripe banana flour and defatted peanut flour. The unripe banana required for the research work was purchased from the local market of Junagadh city. The unripe banana slices and dried were then coarsely ground using a mixture to prepare the flour. The flour was sieved to obtain a uniform particle size. The defatted peanut flour was purchased from Shreenathji Proteins, Rajkot. It was available in a vacuum-packed bag in fine powder form.

Chemical Composition of Raw Materials

The proximate composition of unripe banana flour and defatted peanut flour was assessed using standardized analytical methods. Moisture content was determined by the oven-drying method recommended by AOAC (2005a) [3]. Protein content in both flours and extruded samples was estimated through the Micro-Kjeldahl method based on AOAC (1965) [2]. Fat content was measured using the Soxhlet extraction technique as outlined by AOAC (2005a) [3], while ash content was determined in a muffle furnace following AOAC (2005a) [3] guidelines. Crude fiber was quantified as the organic residue remaining after sequential treatment of the sample with boiling dilute sulphuric acid, boiling dilute sodium hydroxide and alcohol, in accordance with AOAC (2005b) [4]. Total carbohydrates were computed by difference, obtained by subtracting the combined values of moisture, protein, fat, ash and crude fiber (per 100 g) from 100, as suggested by Menezes *et al*., (2015) [26]. These validated methods enabled accurate estimation of key nutritional parameters, ensuring a comprehensive evaluation of the quality and composition of the raw materials.

Experimental Design

Response Surface Methodology (RSM) is a statistical approach employed for empirical modelling through multiple regression analysis, enabling the simultaneous resolution of multivariable equations using quantitative data from well-planned experiments. Its application has been widely reported in the literature on experimental design (Myers, 1976; Khuri and Cornell, 1987; Montgomery, 2017) [31, 23, 29]. In the present investigation, a three-factor, five-level Central Composite Rotatable Design (CCRD) based on a quadratic model was adopted. The independent factors considered were feed moisture content (A), screw speed (B) and die head temperature (C). These factors were coded at five levels: −1.682, −1, 0, + 1 and + 1.682. This design was selected as it provides an efficient framework for studying the combined influence of independent variables on multiple response variables. The coded and actual values of the experimental parameters are summarized in Table 1, while the treatment combinations obtained from the design are provided in Table 2. The chosen methodology ensured a systematic and comprehensive evaluation of the effects of process variables, thereby facilitating optimization of the responses under study.

Table 1: Coded and uncoded values of independent parameters to be used for the preparation of extruded product

Parameter	Code	Coded and Uncoded value				
		-1.682	-1	0	+ 1	+ 1.682
Feed moisture content (% w.b.)	A	12	13.22	15	16.78	18
Screw speed (rpm)	B	200	220	250	280	300
Die head temperature (°C)	C	90	102	120	138	150

Preparation of Unripe Banana Flour

Good-quality, mature but unripe bananas were selected and peeled manually using a stainless-steel knife to avoid contamination. The pulp was uniformly sliced (~3 mm thickness) and dipped in 70 ppm sodium metabisulphite solution for 15 min (Arinola *et al*., 2016) [5] to prevent enzymatic browning and enhance shelf-life. After draining, the slices were dried in a tray dryer at 70 °C with an airflow of ~1.5 m/s until constant weight. The dried slices were then ground into fine flour using a mill and packed in moisture-proof materials for storage.

Table 2: Treatment combinations as per the central composite rotatable design for reparation of extruded product

Run No.	Coded			Uncoded		
	A	B	C	Feed moisture content (%)	Screw speed (rpm)	Die head temperature (°C)
1	0	0	0	15.00	250	120
2	-1	1	-1	13.22	280	102
3	1	1	-1	16.78	280	102
4	0	-1.68	0	15.00	200	120
5	0	0	0	15.00	250	120
6	1.68	0	0	18.00	250	120
7	0	0	-1.68	15.00	250	90
8	0	0	0	15.00	250	120
9	-1	-1	-1	13.22	220	102
10	1	1	1	16.78	280	138
11	0	0	0	15.00	250	120
12	0	0	1.68	15.00	250	150
13	-1	1	1	13.22	280	138
14	0	0	0	15.00	250	120
15	1	-1	-1	16.78	220	102
16	0	0	0	15.00	250	120
17	1	-1	1	16.78	220	138
18	0	1.68	0	15.00	300	120
19	-1.68	0	0	12.00	250	120
20	-1	-1	1	13.22	220	138

Extruded Product Preparation

Extrusion trials were conducted using a co-rotating twin-screw extruder (Basic Technology Pvt. Ltd., Kolkata, India). Prior to extrusion, the machine was conditioned by running it without feed material to remove any residual deposits within the barrel assembly. The heating system was then activated and allowed to stabilize at the required temperatures across the barrel sections. A composite blend of unripe banana flour and defatted peanut flour, mixed in optimized proportions, was prepared by adding the required amount of water to achieve the desired feed moisture content. The mixture was thoroughly blended, sieved to break lumps and obtain a uniform flour sample. For each treatment, 300 g of composite flour was fed into the hopper at a feeder speed of 14 rpm. The extrusion was performed under pre-set process conditions of feed moisture, screw speed and die temperature, which were controlled through the extruder's control panel. The extruder was allowed to run for 30-40 minutes prior to feeding to ensure that the barrel had attained the desired temperature. A round die of 3 mm diameter was used for the extrusion process. The extrudate emerged within approximately 20 seconds of feeding and was cut into desired lengths using the rotating cutter. The samples were then collected on trays, with optional drying applied to products with high moisture content. Finally, the extrudates were packed in zip-lock plastic bags and stored at room temperature until further analysis.

Machine Parameter for Extruded Product

Machine torque

The maximum torque generated in the twin-screw extruder during extrusion process was recorded from digital indicator provided in panel board of extruder (David, 2016) [12]. The machine torque was measured in Nm.

Mass flow rate

Mass flow rate was measured by collecting the extrudates in polyethylene bags for a specific period of time, as soon as it comes out of the die its weight taken instantly after its cooling to ambient temperature (Deshpande and Poshadri, 2011) [13]. The mass flow rate calculated by following formula.

$$\text{Mass flow rate (g/min)} = \frac{\text{Weight of sample collected}}{\text{Time taken to collect sample}}$$

Physical Parameters of Extruded Products

Bulk density

The bulk density of dried extrudates was calculated by determining the volume of extrudates by filling a container of known volume and noting the sample mass. (Mohsenin, 1986) [28]. It was calculated by following formula.

$$\text{Bulk density (g/cm}^3\text{)} = \frac{\text{Weight of extrudates}}{\text{Volume of cyliner}}$$

Specific length

The ratio of length of specimen and the weight of specimen was used to express the specific length (Kanojia and Singh, 2016) [22]. The length of extrudate was determined as the mean of 10 random measurements made with a vernier calliper. The extrudate specific length was calculated by following formula.

$$\text{Specific length (mm/g)} = \frac{\text{Length of specimen}}{\text{Weight of specimen}}$$

Expansion ratio

The ratio of diameter of extrudate and the diameter of die (3 mm) was used to express the expansion of extrudate (Fan *et al*., 1996) [16]. The diameter of extrudate was determined as the mean of 10 random measurements made with a vernier calliper. The expansion ratio was calculated by following formula.

$$\text{Expansion ratio (mm/mm)} = \frac{\text{Extrudate diameter}}{\text{Die diameter}}$$

Statistical Analysis

The impact of three independent variables, namely A (Feed Moisture Content), B (Screw Speed) and C (Die Head Temperature), on different response variables was assessed using Response Surface Methodology (RSM). A Central

Composite Rotatable Design (CCRD) with 3 variables, each at five levels and six centre point combinations, was employed. This approach serves three main purposes: (1) examining the main effects of parameters, (2) establishing models between variables and (3) determining how these variables influence the optimization of selected response variables. Statistical analysis of the experimental data was conducted to observe the significance of the selected process parameters' effects on various responses. The Design Expert software 'DE-13' was employed for regression and graphical analysis of the data. The optimal values for the selected process parameters were determined by solving the regression equation and analysing the response surface contour plots, following the methodology outlined by Khuri and Cornell (1987) [23].

Results and Discussion

Chemical composition of raw material

Table 3: Biochemical characteristics of composite flour

Sr. No.	Characteristic	Value	
		UBF	DPF
1.	Moisture content (% w.b.)	7.00±0.08	5.40±0.15
2.	Total protein (%)	3.02±0.12	52.90±0.65
3.	Fat (%)	0.50±0.03	5.70±0.12
4.	Ash (%)	2.23±0.03	4.58±0.09
5.	Crude fiber (%)	4.34±0.15	6.74±0.22
6.	Total carbohydrates (%)	82.91±0.18	24.68±0.45

Effect of feed moisture content, screw speed and die head temperature on response variables

The treatment-wise data regarding various machine and physical parameters of extruded products prepared by blending of unripe banana flour and defatted peanut flour is presented in the Table 4.

Table 4: Machine and physical characteristics of extruded products

Run No.	Independent variable			Machine parameter		Physical parameter		
	Feed Moisture content (A)% (w.b.)	Screw speed (B) (rpm)	Die head temperature (C) (°C)	Machine Torque (Nm)	Mass flow rate (g/min)	Bulk density (g/cm^3)	Specific length (mm/g)	Expansion ratio
1	15.00	250	120	19	153	0.046	162.33	2.84
2	13.22	280	102	17	161	0.049	152.18	2.81
3	16.78	280	102	17	157	0.0552	130.9	2.38
4	15.00	200	120	21	139	0.0571	109.09	2.41
5	15.00	250	120	18	161	0.0487	161.65	2.81
6	18.00	250	120	15	144	0.0603	121.61	2.30
7	15.00	250	90	23	145	0.0604	114.23	2.31
8	15.00	250	120	16	152	0.0578	162.98	2.79
9	13.22	220	102	23	149	0.0551	123.41	2.49
10	16.78	280	138	12	160	0.0501	155.54	2.85
11	15.00	250	120	16	161	0.0491	161.99	2.85
12	15.00	250	150	14	164	0.0481	155.63	3.08
13	13.22	280	138	13	170	0.0471	171.95	3.29
14	15.00	250	120	18	163	0.0461	162.87	2.88
15	16.78	220	102	21	135	0.0665	91.11	2.13
16	15.00	250	120	17	162	0.0467	160.67	2.86
17	16.78	220	138	15	146	0.0539	118.69	2.58
18	15.00	300	120	15	170	0.0431	162.21	2.99
19	12.00	250	120	21	169	0.0449	163.23	3.07
20	13.22	220	138	19	154	0.0501	145.76	2.94

Machine torque

The experimental study investigated the influence of various process parameters on machine torque in the context of twin-screw extrusion for producing extruded products. Table 4 presents the observed torque values, ranging from 15 to 23 Nm under different treatment conditions. Response surface curves and contour plots in Figure 1 illustrate the impact of independent parameters on machine torque. An increase in feed moisture content initially led to a decrease in machine torque, reaching its lowest point at 15%. However, further increases up to 18% resulted in higher torque levels. Similarly, escalating the screw speed up to its maximum of 300 rpm initially decreased torque, with the minimum observed at 15 Nm using a combination of 15.73% moisture content and 299.91 rpm screw speed. Contour maps indicated that torque decreased with higher feed moisture content until 15.5%, beyond which torque increased. Moreover, raising the die head temperature up to 150 °C initially reduced torque, with the lowest value of 16.24 Nm predicted at 15.75% moisture content and 90.08 °C die head temperature. Further analysis revealed that torque initially decreased with increasing die head temperature up to 120 °C, followed by an increase. The minimum torque of 13.35 Nm was projected for the combination of 300 rpm screw speed and 150 °C die head temperature. Consistent with prior research (Shukla *et al*., 2021) [36], the study confirms that increasing screw speed generally increases torque. Detailed regression analysis and ANOVA results are summarized in Table 5, providing comprehensive insights into the torque dynamics during twin-screw extrusion processes for extruded product preparation.

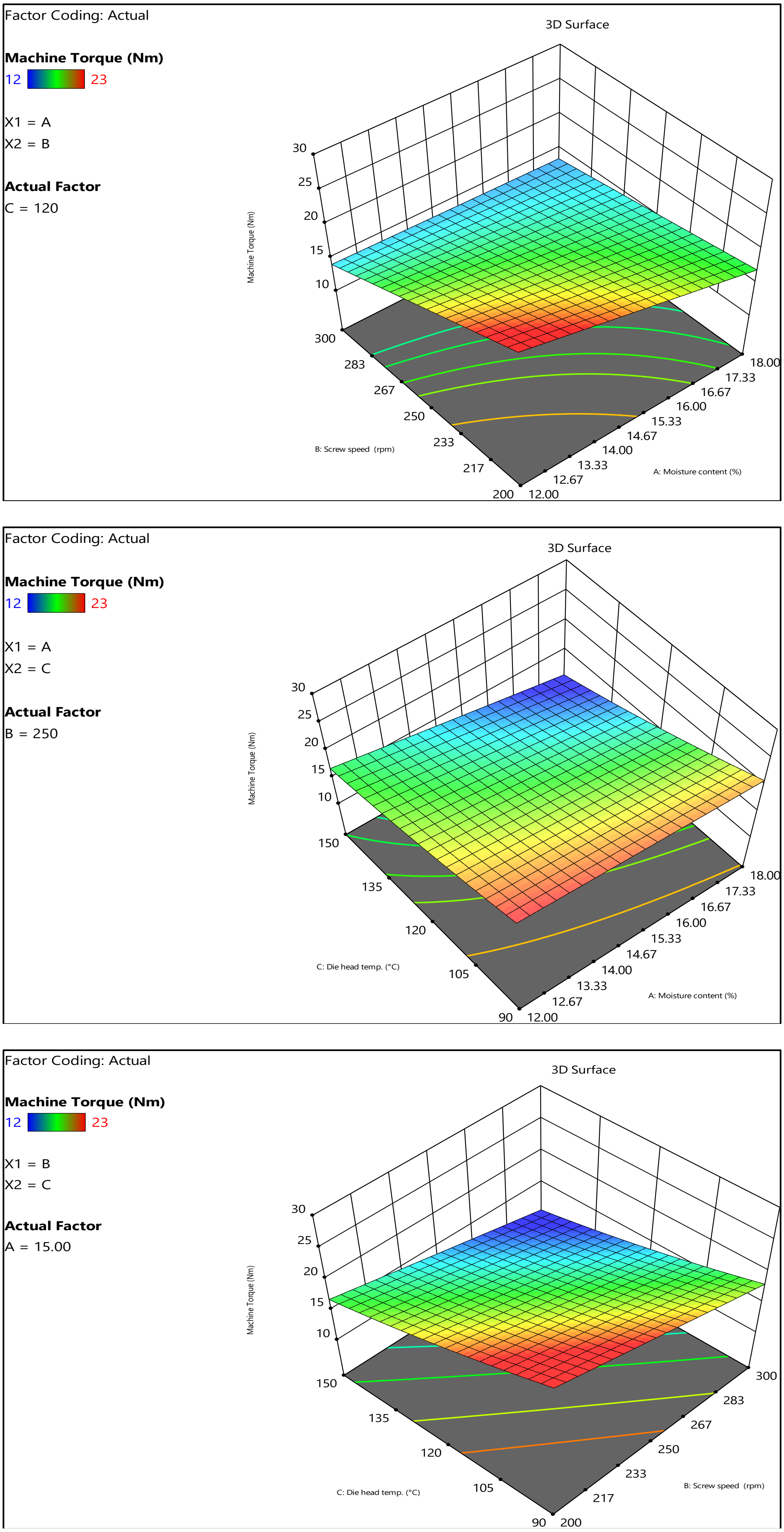
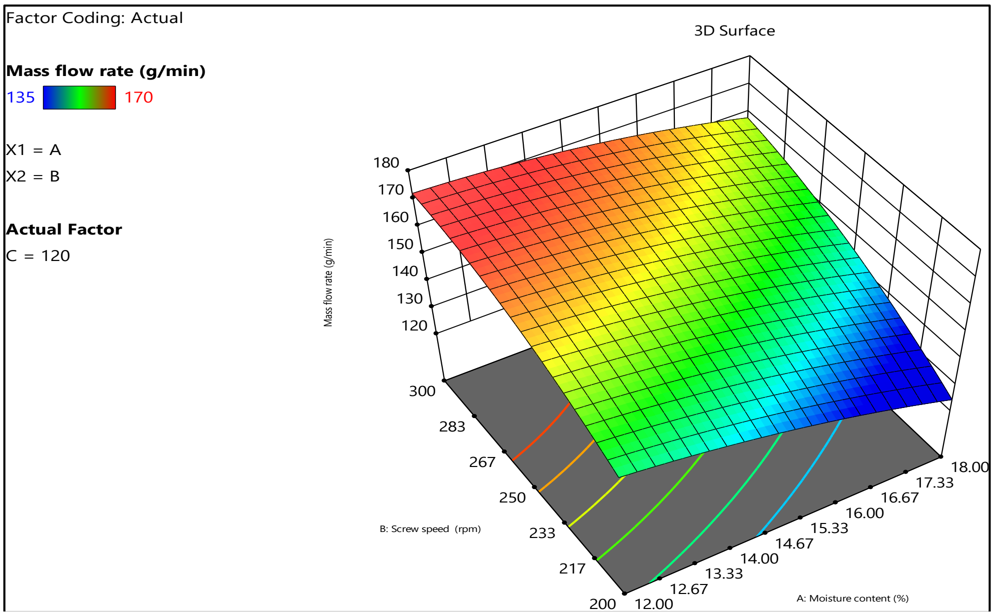
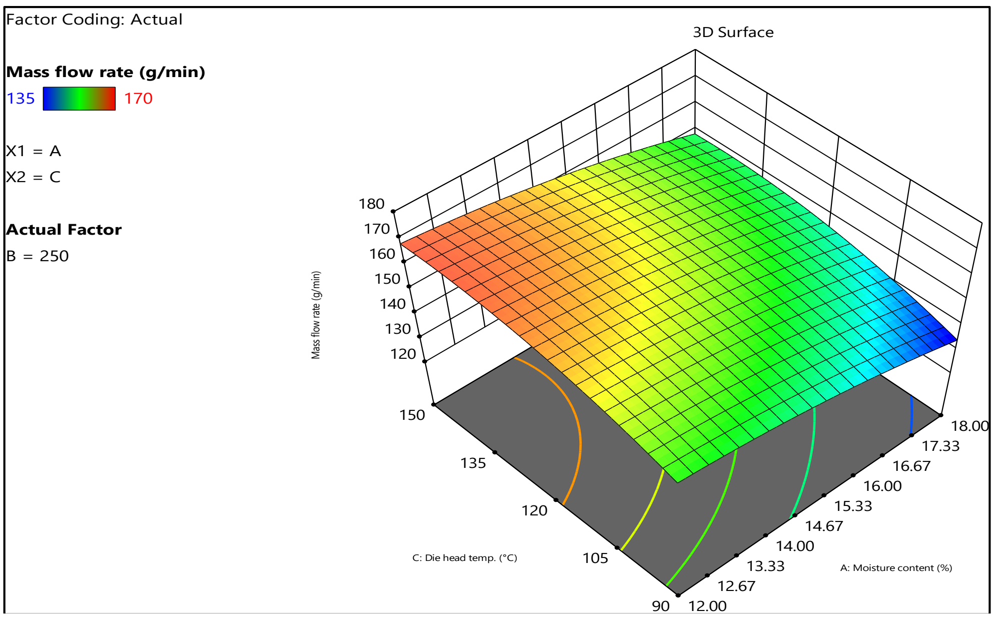


Fig 1: Effect of feed moisture content, screw speed and die head temperature on machine torque

Mass flow rate

The measured values of mass flow rate obtained under different processing conditions during extrusion are presented in Table 4, with values ranging from 135 to 170 g/min. The maximum flow rates were recorded in run numbers 13 and 18, corresponding to the combinations of 13.55% feed moisture, 280 rpm screw speed and 138 °C die head temperature; and 15% feed moisture, 300 rpm screw speed and 120 °C die head temperature, respectively. In contrast, the minimum mass flow rate was obtained in run number 15 under conditions of 16.78% feed moisture, 220 rpm screw speed and 102 °C die head temperature. The response surface plots in Figures 2 illustrate the mass flow rate dynamics of the extruded product as influenced by feed moisture content, screw speed and die head temperature. The mass flow rate generally decreased with increasing feed moisture content, whereas higher screw speed and die head temperature contributed to an increase in the flow rate. The maximum predicted mass flow rate (172.79 g/min) was observed at 12.03% feed moisture content and 300 rpm screw speed, while the minimum predicted value (124.89 g/min) was recorded at 17.97% feed moisture content and 200 rpm screw speed. Similarly, the interaction of feed moisture and die head temperature showed that mass flow rate increased up to a die head temperature of 143 °C at lower moisture levels, reaching 168.40 g/min at around 12.03% feed moisture, but decreased thereafter with higher moisture or lower temperature, with the minimum value of 134.50 g/min observed at 17.95% moisture and 90 °C die head temperature. The combined influence of screw speed and die head temperature revealed a steady rise in mass flow rate with increasing levels of both parameters, with the highest predicted value of 170.14 g/min obtained at 300 rpm screw speed and 140 °C die head temperature, while the lowest predicted value (126.96 g/min) occurred at 201 rpm screw speed and 91 °C die head temperature. These findings are consistent with earlier reports by Shruthi *et al.* (2017) [35], who noted that higher die head temperatures reduce the viscosity of feed material, thereby improving flow characteristics and resulting in enhanced mass flow rates under elevated temperature conditions. Detailed regression analysis and ANOVA results for the mass flow rate are summarized in Table 5 providing comprehensive insights into the effects of extrusion variables on mass flow rate during twin-screw extrusion.





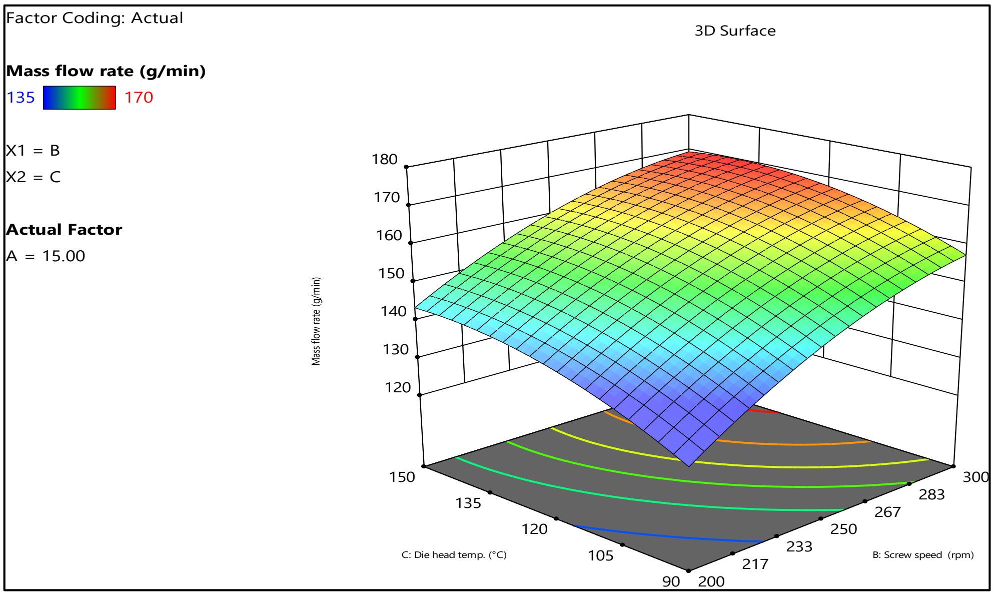
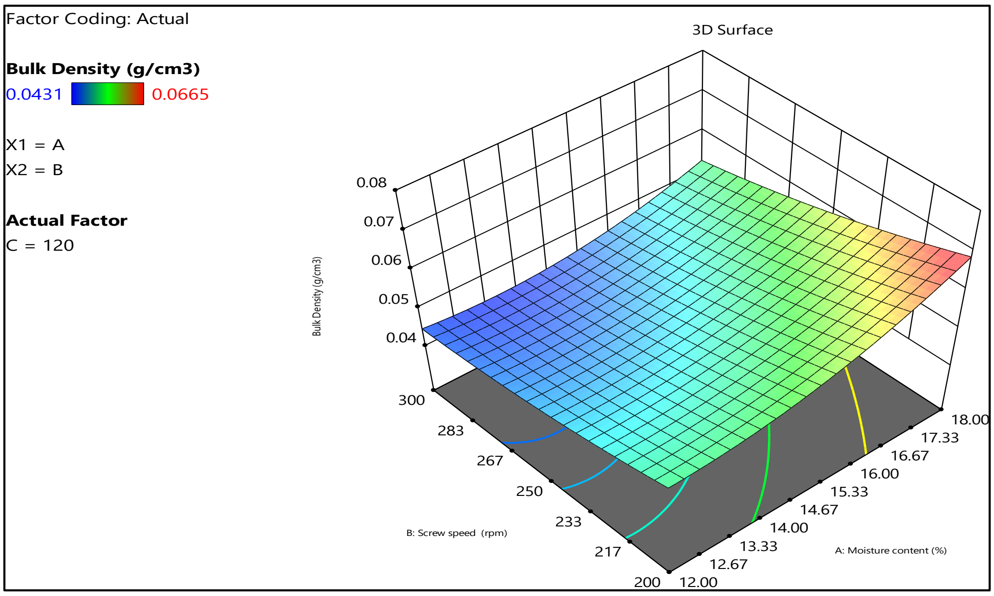


Fig 2: Effect of feed moisture content, screw speed and die head temperature on mass flow rate

Bulk density

Table 4 displays experimental bulk density values obtained from various processing conditions during the production of extruded products. The bulk density ranged between 0.0431 g/cm³ to 0.0665 g/cm³. The highest value of 0.0665 g/cm³ was observed in run number 15 at 16.78% feed moisture content, 220 rpm screw speed and 102 °C die head temperature. In contrast, the lowest bulk density of 0.0431 g/cm³ was recorded in run number 18 corresponding to 15% feed moisture content, 300 rpm screw speed and 120 °C die head temperature. Figures 3 illustrate the response surface and contour plots depicting the variations in bulk density. Increasing screw speed up to 300 rpm generally decreased bulk density, particularly when coupled with lower feed moisture levels. For instance, at 13.41% moisture content and 300 rpm screw speed, bulk density was predicted to decrease to approximately 0.043 g/cm³. However, higher feed moisture content at lower screw speeds led to denser extrudates, confirming the strong influence of moisture and mechanical shear on product compactness. Similarly, bulk density decreased with decreasing feed moisture and increasing die head temperature up to moderate levels. The lowest predicted bulk density of 0.046 g/cm³ was obtained at 13.12% feed moisture content and 127.24 °C die head temperature. The combined effect of screw speed and die head temperature also revealed that bulk density decreased with increasing values of both parameters up to an optimum point, beyond which further increases tended to stabilize. The minimum predicted bulk density of about 0.044 g/cm³ occurred at 300 rpm screw speed and 125 °C die head temperature. These observations clearly demonstrate that extrusion parameters significantly influenced the structural integrity and packing density of the product. The present findings are in close agreement with those reported in earlier studies. Shruthi *et al.* (2017) [35] observed a decline in bulk density with increasing die temperatures, while Sapariya *et al.* (2022) [34] confirmed that higher feed moisture content produced denser extrudates. Baik *et al.* (2004) [6] attributed this to reduced elasticity and increased plasticization at higher moisture levels, which restrict expansion. Ding *et al.* (2006) [15] further demonstrated that elevated die temperatures enhance expansion through greater moisture evaporation, thereby lowering product density. Table 5 presents the regression and ANOVA results for a more detailed understanding of bulk density variations in extruded products.



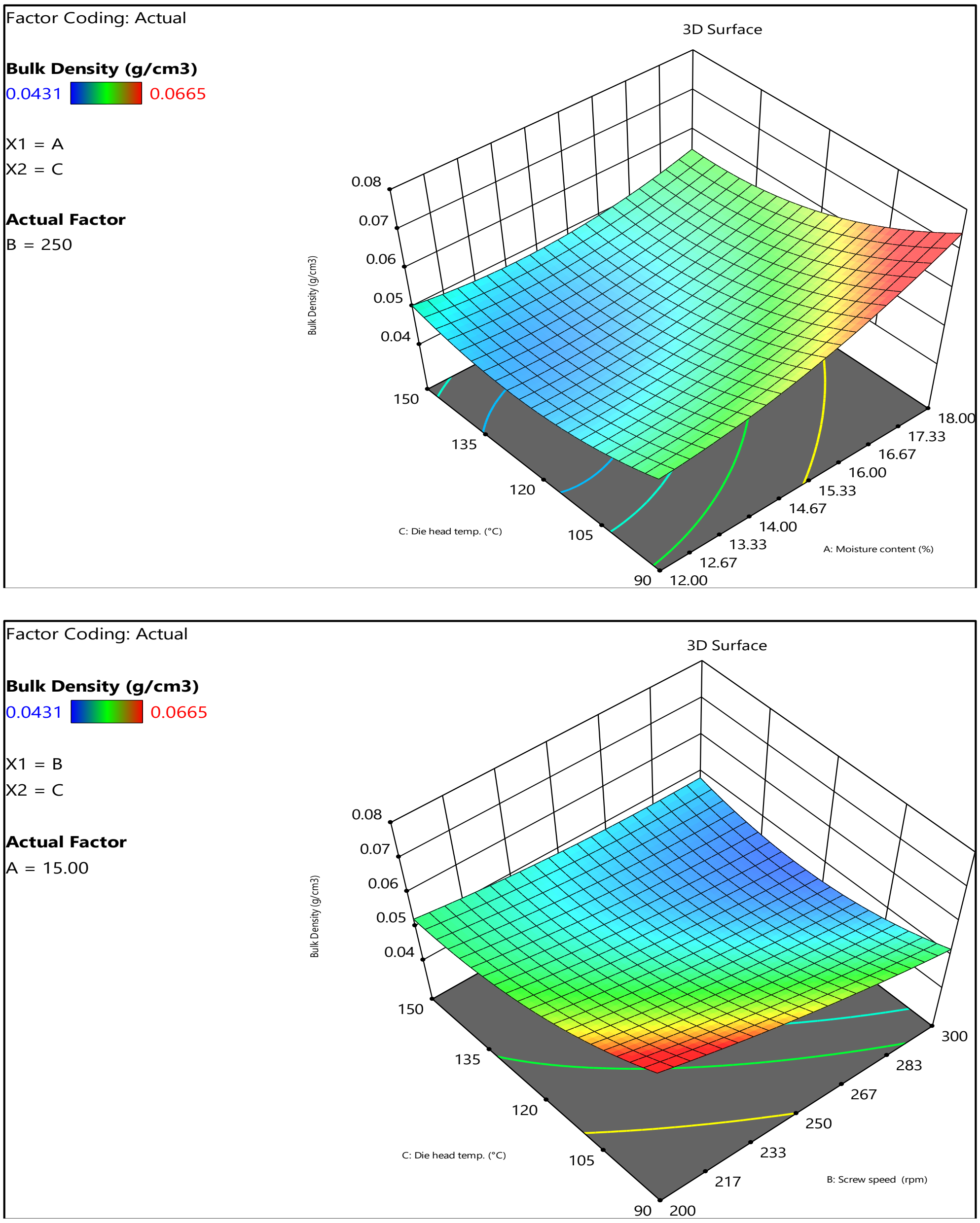


Fig 3: Effect of feed moisture content, screw speed and die head temperature on bulk density

Specific length

Table 4 displays experimental specific length values obtained from various processing conditions during the production of extruded products. The specific length ranged between 91.11 mm/g to 171.95 mm/g. The highest value of 171.95 mm/g was observed in run number 13 at 13.22% feed moisture content, 280 rpm screw speed and 138 °C die head temperature. In contrast, the lowest specific length of 91.11 mm/g was recorded in run number 15 under conditions of 16.78% feed moisture content, 220 rpm screw speed and 102 °C die head temperature. Figures 4 illustrate the response surface and contour plots showing the variations in specific length under different process variables. Increasing screw speed up to 273 rpm and reducing feed moisture content to about 13.70% generally enhanced specific length, with the maximum predicted value reaching 172.70 mm/g. Conversely, higher feed moisture combined with lower screw speeds resulted in shorter extrudates. Similarly, specific length increased with decreasing feed moisture content and increasing die head temperature up to an optimum level. The maximum predicted specific length of 170.57 mm/g was obtained at 13.55% feed moisture content and 130 °C die head temperature, whereas higher feed moisture and lower die head temperature conditions produced shorter products. The combined effect of screw speed and die head temperature revealed that specific length increased with increasing values of both parameters up to a certain point, beyond which the effect stabilized. The highest predicted specific length of 172.98 mm/g was recorded at 274.82 rpm screw speed and 130.59 °C die head temperature. These observations confirm the strong influence of extrusion parameters on the elongation and structural properties of extrudates. The present findings are supported by earlier studies. Yatin *et al.* (2015) [43] reported that increased moisture content promotes plasticization, enabling extrudates to elongate further and thereby enhancing specific length. Bhople and Singh (2017) [7] also observed that higher barrel temperatures improved flow characteristics, contributing to greater stretching and longer product length. These results highlight the importance of optimizing feed moisture and die temperature to achieve extrudates with desirable structural properties. Table 5 presents the regression and ANOVA results for further insights into variations in specific length of extruded products.

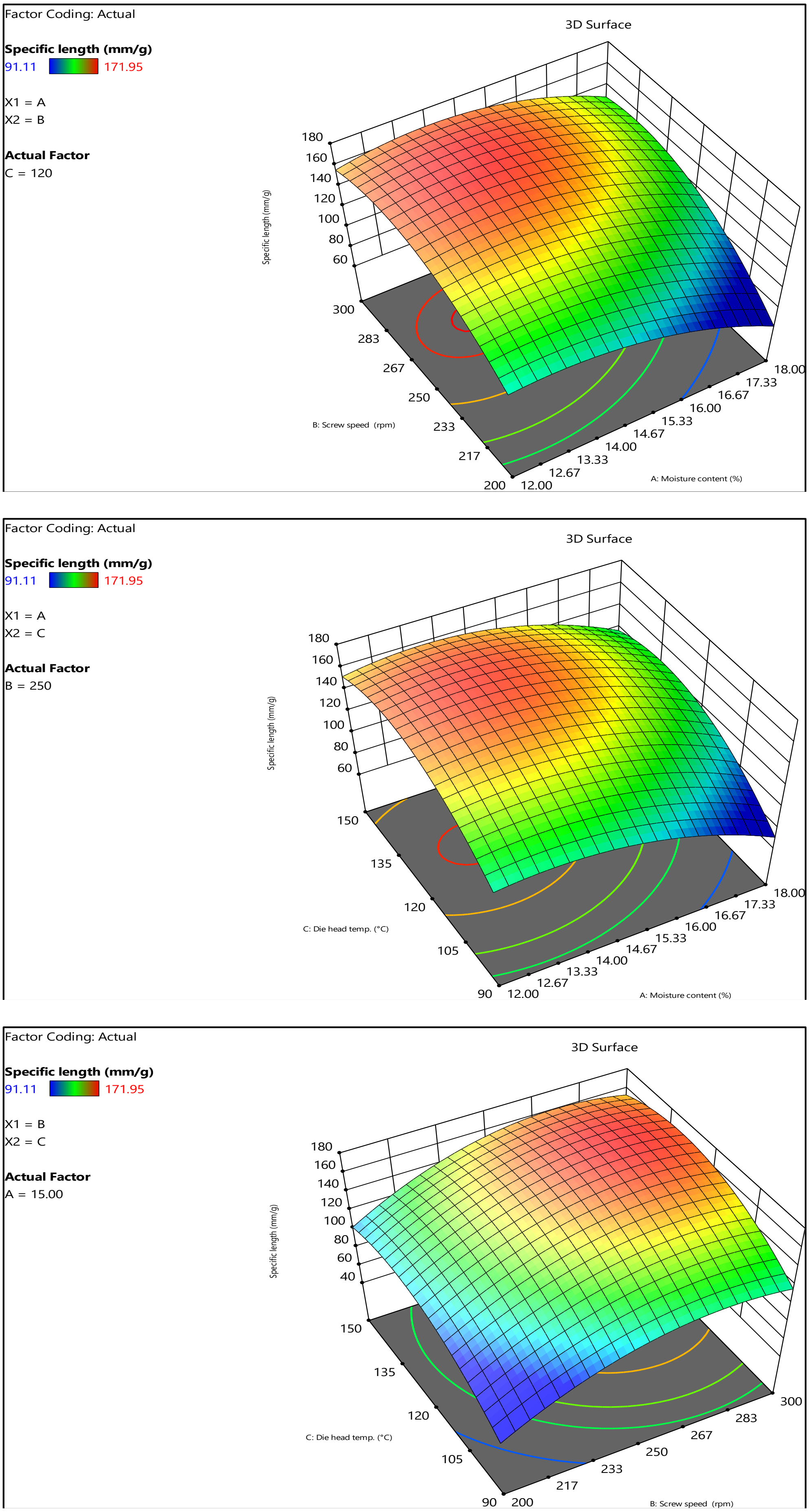


Fig 4: Effect of feed moisture content, screw speed and die head temperature on specific length

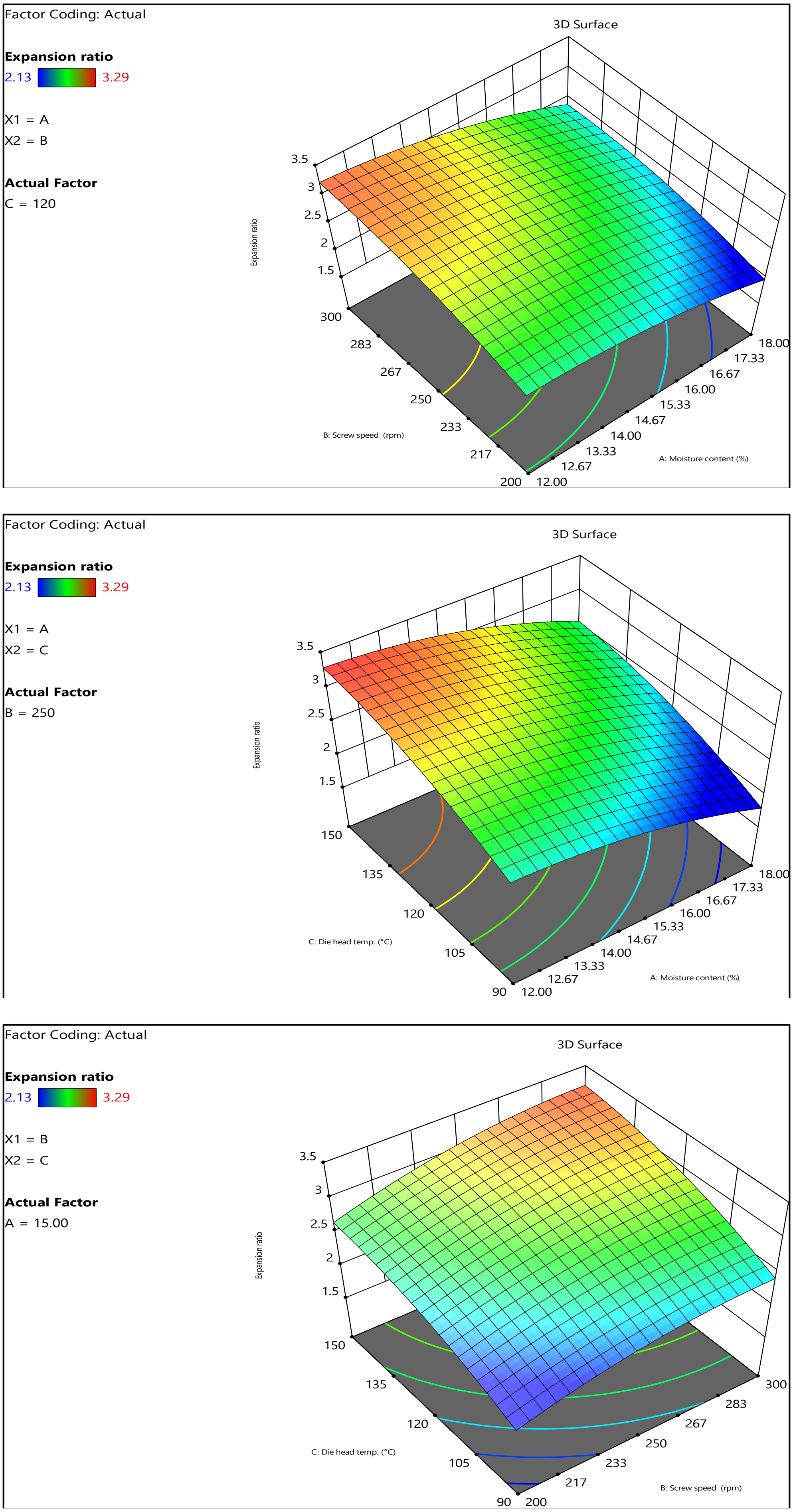


Fig 5: Effect of feed moisture content, screw speed and die head temperature on expansion ratio

Expansion ratio

The experimental values for the expansion ratio of the extruded products obtained under different processing conditions are summarized in Table 4. The expansion ratio was found to range between 2.13 and 3.29. The maximum expansion ratio of 3.29 was recorded in Run 13, corresponding to the combination of 13.22% feed moisture content, 280 rpm screw speed and 138 °C die head temperature, while the minimum value of 2.13 was obtained in Run 15 under the conditions of 16.78% feed moisture content, 220 rpm screw speed and 102 °C die head temperature. These observations highlight the significant influence of feed moisture, screw speed and die head temperature on the expansion behaviour of the extrudates. The response surface and contour plots in Figure 5 further illustrate the effects of these parameters on expansion ratio. The results revealed that expansion ratio generally increased with lower feed moisture content and higher screw speed. The maximum predicted expansion ratio of 3.22 was achieved at approximately 12.01% feed moisture content and 299 rpm screw speed, while the lowest predicted value was associated with higher feed moisture levels and moderate screw speeds. Similarly, the interaction of feed moisture and die head temperature indicated that expansion ratio improved with decreasing moisture and rising die head temperature, attaining a maximum predicted value of 3.28 at around 12.12% feed moisture content and 149 °C die head temperature. At higher moisture levels or lower die head temperatures, the expansion ratio showed a marked reduction, reaching its lowest values under such combinations. The combined effect of screw speed and die head temperature revealed that expansion ratio increased progressively with increases in both factors, with the maximum predicted value of 3.22 observed at 298 rpm screw speed and 150 °C die head temperature. These findings align with earlier studies, where Gat and Ananthanarayan (2015) [17] reported that increasing feed moisture reduced the expansion of extrudates, while high die head temperatures caused a slight reduction in expansion. Similarly, Stojceska *et al.* (2009) [37] observed that greater screw speed enhanced expansion ratio due to increased starch gelatinization at elevated temperatures, which reduced melt viscosity and facilitated bubble growth, thereby improving the expansion of extruded products. Table 5 presents the regression and ANOVA results for further insights into variations in expansion ratio of extruded products.

Empirical Models

The derived model, giving the empirical relation between the response variables and test variables in coded units, was obtained as under:

$\text{Machine torque} = 17.368 - 1.25 * A - 2.13 * B - 2.5 * C + 0.625 * AB - 0.3750 * AC + 0.1250 * BC + 0.0052 * A^2 + 0.0052 * B^2 + 0.1820 * C^2$

$\text{Mass flow rate} = 158.70 - 5.71 * A + 8.50 * B + 4.39 * C + 1.00 * AB + 0.00 * AC - 0.50 * BC - 0.967 * A^2 - 1.67 * B^2 - 1.67 * C^2$

$\text{Bulk density} = 0.049 + 0.0037 * A - 0.0035 * B - 0.0033 * C - 0.0008 * AB - 0.0014 * AC + 0.0013 * BC + 0.0014 * A^2 + 0.0005 * B^2 + 0.0020 * C^2$

$\text{Specific length} = 162.08 - 12.23 * A + 16.18 * B + 12.01 * C + 2.71 * AB + 1.26 * AC - 0.69 * BC - 6.95 * A^2 - 9.34 * B^2 - 9.60 * C^2$

$\text{Expansion ratio} = 2.84-0.211 * A + 0.158 * B + 0.230 * C - 0.0188 * AB - 0.0013 * AC + 0.0062 * BC - 0.054 * A^2 - 0.049 * B^2 - 0.0508 * C^2$

Where, A, B and C are the coded factors of feed moisture content, screw speed and die head temperature, respectively.

Table 5: ANOVA table and regression coefficients for response surface quadratic model of different machine and physical characteristics of extruded products

Source	Machine torque (Nm)	Mass flow rate (g/min)	Bulk density (g/cm^3)	Specific length (mm/g)	Expansion ratio
Intercept	17.37	158.70	0.0490	162.08	2.84
Linear terms					
A	-1.25**	-5.71**	0.0037**	-12.23***	-0.2112***
B	-2.13***	8.50***	-0.0035**	16.18***	0.1586***
C	-2.50***	4.39**	-0.0033**	12.01***	0.2303***
Interaction terms					
AB	0.6250	1.0000	-0.0008	2.71***	-0.0188
AC	-0.3750	0.0000	-0.0014	1.26**	-0.0013
BC	0.1250	-0.5000	0.0013	-0.6900*	0.0062
Quadratic terms					
A^2	0.0052	-0.9674	0.0014	-6.95***	-0.0544***
B^2	0.0052	-1.67	0.0005	-9.34***	-0.0491***
C^2	0.1820	-1.67	0.0020	-9.60***	-0.0508***
Indicators for model fitting					
R^2	0.9182	0.9053	0.8392	0.9994	0.9942
Adj-R^2	0.8446	0.8200	0.6946	0.9989	0.9889
Pred-R^2	0.6174	0.6323	0.6134	0.9977	0.9747
Adeq Precision	13.3770	12.1732	9.1522	145.177	52.6535
F-value	12.47	10.62	5.80	1866.74	189.88
Lack of fit	NS	NS	NS	NS	NS
C.V.%	7.11	2.78	6.64	0.5453	1.18

Optimization and Validation of Process Variables

The optimum extrusion conditions for blending unripe banana flour and defatted peanut flour were determined through numerical optimization using Design Expert software version 13 (State Ease Inc., Minneapolis, MN, USA). The applied criteria and constraints are summarized in Table 6. In the optimization process, equal weightage (importance = 3) was assigned to all independent variables and responses, except for the expansion ratio, which was given the highest priority with an importance value of 5. The optimized conditions obtained were 13% feed moisture content (w.b.), screw speed of 270 rpm and die head temperature of 117 °C. To validate the model, experimental trials were conducted under these optimized conditions. The observed responses were in close agreement with the predicted values (Table 6), indicating a high degree of model accuracy. This close correspondence between predicted and experimental results confirmed the adequacy of the regression models and the effectiveness of the optimized process parameters in producing extruded products with desirable quality attributes.

Table 6: Constraints, criteria and output for numerical optimization of extruded products

Variables					
Constraint		**Goal**	**Imp.**	**Optimum value**	**Exp. Value**
Feed moisture content (%w.b.)		In the range	3	13.216	13
Screw speed (rpm)		In the range	3	269.85	270
Die head temperature (°C)		In the range	3	117.07	117
Response					
Constraint	**Goal**	**Imp.**	**Predicted value**	**Experimental Value**	**Deviation (%)**
Machine torque (Nm)	None	3	17.13	16.30	4.84
Mass flow rate (g/min)	None	3	166.99	162.01	2.98
Bulk density (g/cm^3)	None	3	0.045	0.040	11.11
Specific length (mm/g)	Maximum	3	170.235	175.32	-2.99
Expansion ratio	Maximum	5	3.052	3.01	1.38

Conclusion

The study established that unripe banana flour (UBF) and defatted peanut flour (DPF) can be effectively blended to produce nutritionally enriched extruded snacks with desirable physical properties. Feed moisture content, screw speed and die head temperature significantly influenced torque, mass flow rate, bulk density, specific length and expansion ratio. Using RSM-based optimization, the ideal conditions were identified as 13.21% feed moisture, 270 rpm screw speed and 117 °C die head temperature, yielding experimental values closely matching predictions with minimal deviation. These findings highlight the potential of UBF-DPF blends for developing protein-and fiber-rich ready-to-eat extruded products with commercial application.

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