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RESPONSE SURFACE MODELLING FOR PREPARATION OF EXTRUDED SNACKS BY BLENDING OF PEARL MILLET AND DEFATTED PEANUT FLOUR

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ABSTRACT

Response surface modelling approach was applied for the extruded snacks by blending of pearl millet flour with defatted peanut flour using a twin-screw extruder. Optimized through Mixture Design of Response Surface Methodology (RSM). The Central Composite Rotatable Design (CCRD) with 3 variables each at 5 levels was employed for the optimization of processing parameters *viz.*, feed moisture content, screw speed and die head temperature. Modelling and optimization of processing parameters carried out on the basis of effect of two independent variables on dependent parameters while keeping third independent variable constant at its centre point. From the regression analysis and ANOVA results the empirical model was formulated to express the relationship between different machine parameters (machine torque and mass flow rate) and physical parameters (bulk density, specific length and expansion ratio) and the test variables. The regression models that explained the significant effects of different levels on all the response variables were determined. The results showed that the extrusion variables significantly influenced ($p<0.05$) the quality characteristics of extruded product. The developed regression model of all the responses had a sufficient high coefficient of determination R^2 and adjusted R^2 value indicating the adequacy, good fit and high significance of the model. The good fits of the response models were affirmed favourably as the calculated F-value was significant ($p<0.001$) for all dependent parameters and at the same time, it possessed non-significant lack of fit ($p>0.05$) and the small value of coefficient of variation for all dependent parameters explained that the experimental results were precise and reliable. Hence, this works favoured the use of pearl millet and defatted peanut flour in snack manufacturing. It highlighted the potential benefits of these ingredients in enhancing the nutritional profile of snacks while maintaining high standards of product quality and appeal to consumers. Optimizing flour proportions and processing parameters showed how these flours can be used effectively to create snacks that are both nutritious and appealing to the market.

Key words : Defatted peanut flour, Extruded product, Pearl millet flour, Response surface modelling.

Introduction

The global food industry is under increasing pressure to produce healthy, sustainable, and nutrient-dense snacks to meet the needs of health-conscious consumers. The focus is now shifting to alternative raw materials that can contribute to both the nutritional value and overall quality of food products. Pearl millet (*Pennisetum glaucum*), an ancient grain, is a rich source of fiber, protein, and micronutrients like iron, magnesium, and zinc, and has been recognized for its ability to grow in harsh, arid environments (Singh *et al.*, 2018; Balasubramanian and Viswanathan, 2010). Its incorporation into food products is particularly beneficial in developing countries where malnutrition is a persistent issue. On the other hand, defatted peanut flour, a by-product of peanut oil extraction, offers an excellent source of plant-based protein and is becoming increasingly important for food fortification in protein-deficient populations (Olayanju *et al.*, 2019; Dixit *et al.*, 2011).

Extrusion cooking is a versatile technology used in food processing, capable of producing various ready-to-eat snacks with desirable sensory characteristics such as crispiness, puffing and lightness. The extrusion process subjects raw materials to heat, pressure, and mechanical shear, resulting in the gelatinization of starch, denaturation of proteins and formation of expanded, porous structures (Ilo and Berghofer, 2003; Bhat and Bhat, 2013). The use of twin-screw extruders provides further flexibility in the processing of complex blends like pearl millet and defatted peanut flour. By optimizing key extrusion parameters *viz*., feed moisture content, screw speed and die head temperature, the physical and nutritional properties of the extruded products can be controlled.

The present study aims to explore the development of extruded snacks by blending pearl millet flour with defatted peanut flour using twin-screw extrusion. A Response Surface Modelling (RSM) approach was employed to optimize the blend ratios and processing conditions to maximize the quality of the final product. This research provides insights into the effects of processing parameters on product qualities such as bulk density, expansion ratio, and specific length, ultimately contributing to the production of high-quality, nutritious snacks with enhanced market appeal.

Materials and Methods

Raw materials

The preparation of extruded products in this study primarily involved two essential constituents: pearl millet flour and defatted peanut flour. The pearl millet was procured from a local market in Junagadh, where it underwent a meticulous cleaning process to remove all impurities. After cleaning, the millet was coarsely ground using a traditional stone mill, which helps in preserving the flour's nutritional integrity. The resulting flour was then sieved to ensure a uniform particle size, critical for the extrusion process. To maintain its freshness and quality, the flour was packed in a polyethylene bag and stored in a refrigerator. Defatted peanut flour was procured from its manufacturer in vacuum-packed bags as a fine powder. The flour was stored in airtight containers to maintain their moisture content prior to extrusion trials. This form of the flour enhances its usability in the extrusion process while retaining its nutritional benefits. The flour blends were stored in airtight containers to maintain their moisture content prior to extrusion trials. Extrusion trials were performed using a co-rotating laboratory twin-screw extruder at Department of Processing and Food Engineering, College of Agricultural Engineering and Technology, Junagadh Agricultural University, Junagadh.

Experimental design

Experimental trials were conducted to optimize the proportions of pearl millet flour and defatted peanut flour for producing extruded products. The flours were blended in various ratios as outlined in Table 1, following the Mixture Design of Response Surface Methodology (RSM). To ensure uniformity for extrusion cooking, the flours were mixed thoroughly, and water was added to achieve the desired moisture content. The extrusion process was carried out with specific conditions: a feed moisture content of 16%, a feeder temperature of 60°C, a barrel temperature of 100°C, a die head temperature of 135°C and a screw rotation speed of 250 rpm, using a twin-screw extruder (Davara *et al*., 2022). The extruded products, resulting from various flour combinations, were then evaluated for sensory attributes, using a 9-point hedonic scale. Following the sensory evaluation, RSM was utilized to optimize the flour proportions based on the sensory scores obtained from the different extruded products. The final optimized formulation of the composite flour was selected for further refinement of the processing conditions, focusing on enhancing various physical parameters of the extruded products along with machine parameters.

A Central Composite Rotatable Design (CCRD) was used within the framework of Response Surface Methodology (RSM) with 3 variables each at 5 levels as shown in Table 2 was employed for the optimization of processing parameters *viz.*, feed moisture content, screw speed and die head temperature and to investigate the effects of extrusion on processing parameters. Three independent variables i.e., feed moisture content (12-18%), screw speed (200-300 rpm), and die head temperature (900-150°C) were selected and the design matrix generated by the CCRD resulted in a total of 20 experimental runs as described in Table 3 (Montgomery, 2017; Goyal and Sharma, 2009).

Extrusion processing

The twin-screw extruder used in this study was equipped with independently controlled temperature zones and an adjustable screw speed. Flour blends were fed into the extruder at varying feed moisture contents from the feed hopper. During extrusion, the moisture content, screw speed and die head temperature were set as per the requirement on the control panel. The extrudates were collected at the die head, cooled at room temperature, and analyzed for their physical parameters, including bulk density, specific length, and expansion ratio.

Physical and Machine Parameters of extrudates

The physical parameters of the extrudates were measured using standard methods. Bulk density was determined by measuring the mass of extrudates in a known volume (Anderson *et al*., 1969). Expansion ratio

Table 1 : Treatment details for optimization of flour proportion.

Treatment No.	Pearl millet flour (%)	Defatted peanut flour (%)	Total
1	36.67	63.33	100.00
2	63.33	36.67	100.00
3	90.00	10.00	100.00
4	10.00	90.00	100.00
5	10.00	90.00	100.00
6	30.00	70.00	100.00
7	70.00	30.00	100.00
8	90.00	10.00	100.00
9	90.00	10.00	100.00
10	50.00	50.00	100.00
11	10.00	90.00	100.00
12	50.00	50.00	100.00
13	50.00	50.00	100.00

was calculated as the ratio of the diameter of the extrudates to the diameter of the die opening (here 3 mm) (Fan *et al.*, 1996). Specific length was calculated by dividing the length of the extrudates by their mass (Kanojia and Singh, 2016).

The machine parameters of the extruded i.e., torque was recorded from the digital indicator on the control panel display. The machine torque was measured in Nm. The mass flow rate of the extrudates was measured by collecting them in polyethylene bags over a specified time period. As the extrudates exited the die, their weight was recorded immediately after they cooled to ambient temperature (Deshpande and Poshadri, 2011). This method allowed for an accurate determination of the mass flow rate, which is crucial for evaluating the extrusion process's efficiency and product output.

Each measurement was repeated in triplicate and the mean values were reported.

Statistical analysis

The experimental data were analyzed using regression analysis to develop empirical models that describe the relationships between the independent variables and response variables. Analysis of variance (ANOVA) was performed to determine the significance of the regression models and individual terms. The

Table 2 : Coded and uncoded values of independent parameters to be used in the optimization of processing condition for the preparation of extruded product.

Parameter	Code	Coded and Uncoded value				
		-1.682	-1	0	+1	+1.682
Feed moisture content (%)	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

Table 3 : Treatment combinations as per the central composite rotatable design for preparation of extruded product.

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

adequacy of the models was assessed using the coefficient of determination (R^2) and adjusted R^2 values. Lack of fit tests were conducted to ensure the model's accuracy and reliability in predicting the experimental outcomes (Khuri and Cornell, 1987).

Results and Discussion

Physical and Machine Parameters

The results of the study indicated that the extrusion process variables significantly influenced the physical parameters of the extruded snacks. Feed moisture content, screw speed, and die head temperature all had a marked impact on the expansion ratio, bulk density, and specific length of the extrudates. The regression analysis and ANOVA outcomes for the different parameters of the extruded product are presented in Table 4. From these results, the empirical model was formulated to express the relationship between different physical and machine parameters and the test variables in coded units.

Bulk density

The regression equation for bulk density reveals that moisture content (A) and screw speed (B) slightly increase bulk density, as indicated by their positive coefficients (0.0015 and 0.0026, respectively). Die head temperature (C), however, has a significant negative effect on bulk density (-0.0103). Interaction terms such as AC (-0.0108) and BC (-0.0067) further reduce bulk density, suggesting that combinations of moisture and die head temperature or screw speed and die head temperature have compounded negative effects. The quadratic term for moisture content (A^2) has a positive coefficient (0.0065), indicating that bulk density increases at higher moisture levels, whereas the quadratic term for screw speed (B^2) negatively impacts bulk density (-0.0043), showing that very high screw speeds lead to a reduction in bulk density.

$$\text{Bulk density} = 0.0776 + 0.0015 * A + 0.0026 * B - 0.0103 * C + 0.0005 * AB - 0.0108 * AC * 0.0067 * BC + 0.0065 * A^2 - 0.0043 * B^2 + 0.0014 * C^2 \qquad (1)$$

The R^2 value of 0.8824 indicates that 88.24% of the variation in bulk density is explained by the model. The adjusted R^2 of 0.7765 suggests that the model is a good fit, accounting for the number of predictors. The predicted R^2 of 0.3145 is relatively low, which implies that while the model fits the data well, its predictive ability could be improved. The adequate precision of 10.9835 indicates the model can be used for optimization. The F-value of 8.33 shows that the model is statistically significant, and the lack of fit is non-significant, affirming the adequacy of the model. The C.V. of 8.96% indicates reasonable experimental precision for bulk density.

In summary, the regression analysis indicates that while moisture content and screw speed generally increase bulk density, die head temperature has a significant reducing effect. The interaction between these factors and their non-linear impacts provides a more comprehensive understanding to optimize extrusion conditions to achieve the desired bulk density in extruded products. Bulk density, a critical parameter for determining product texture and consumer acceptability, decreased with increasing screw speed and die head temperature. This reduction in bulk density is consistent with findings from other extrusion studies that have shown lower densities for products with greater expansion (Lue *et al.*, 1991; Jacob and Leelavathi, 2007). As expected, higher feed moisture content led to denser extrudates, due to the reduced expansion and tighter internal structure of the extruded product.

Specific length

For specific length, the linear terms indicate that screw speed (B) and die head temperature (C) positively affect specific length, with coefficients of 1.89 and 9.82, respectively. This means that increasing either screw speed or die head temperature results in longer extrudates. However, moisture content (A) slightly decreases specific length, with a coefficient of -0.3185. Interaction effects between the factors are minimal, except for AB, which shows a slight negative effect (-0.5375). The quadratic terms for moisture (A^2, -2.05) and screw speed (B^2, -2.61) reveal that high levels of these variables decrease specific length. The temperature quadratic term (C^2) shows a larger negative effect (-4.89), indicating that very high temperatures can significantly reduce specific length.

$$\text{Specific length} = 113.48 * 0.3185 * A + 1.89 * B + 9.82 * C - 0.5375 * AB + 0.3950 * AC * 0.0800 * BC - 2.05 * A^2 + 2.61 * B^2 - 4.89 * C^2 \qquad (2)$$

The R^2 value of 0.9411 shows that 94.11% of the variability in specific length is explained by the model, indicating excellent fit. The adjusted R^2 of 0.8881 further confirms that the model is well-fitted to the data. The predicted R^2 of 0.6339 suggests good predictive accuracy for specific length. The adequate precision of 13.8869 indicates a strong signal and the model is adequate for optimization. The F-value of 17.76 shows high statistical significance, while the non-significant lack of fit confirms that the model fits the data well. The C.V. of 3.15% indicates very precise measurements for specific length.

Specific length was another parameter influenced by extrusion variables. Higher screw speeds and lower feed moisture content produced extrudates with greater

Table 4 : ANOVA table and regression coefficients for response surface quadratic model of different physical parameters of extruded products.

Source	Bulk density (g/cm^3)	Specific length (mm/g)	Expansion ratio	Machine torque (Nm)	Mass flow rate (g/min)
Intercept	0.0776	113.48	2.86	16.70	171.75
Linear terms					
A	0.0015	-0.3185	-0.0945**	-0.6124*	3.31**
B	0.0026	1.89	0.0375	-1.17***	-0.1964
C	-0.0103**	9.82***	0.1487***	-0.0732	0.8820
Interaction terms					
AB	0.0005	-0.5375	0.0238	-0.1250	-2.13
AC	-0.0108**	0.3950	-0.0012	0.1250	-3.13*
BC	-0.0067*	-0.0800	0.0188	-0.1250	-2.38
Quadratic terms					
A2	0.0065**	-2.05*	-0.1261***	1.32***	-6.09***
B2	-0.0043*	-2.61*	0.0861**	0.0865	1.52
C2	0.0014	-4.89**	-0.0306	-0.0903	-2.02
Indicators for model fitting					
R^2	0.8824	0.9411	0.9430	0.8875	0.8703
Adj-R^2	0.7765	0.8881	0.8918	0.7862	0.7535
Pred-R^2	0.3145	0.6339	0.6954	0.2611	0.5837
Adeq Precision	10.9835	13.8869	16.3996	11.5074	10.2570
F-value	8.33	17.76	18.39	8.76	7.45
Lack of fit	NS	NS	NS	NS	NS
C.V.%	8.96	3.15	2.52	4.54	2.26

A= Feed moisture content, B=Screw speed, C= Die head temperature

***Significant at $p<0.001$, **Significant at $p<0.01$, *Significant at $p<0.05$, S = Significant, NS = non-significant.

specific lengths, indicating the production of light and elongated products (Singh *et al.*, 2007; Anandharamakrishnan and Padma Ishwarya, 2015). The regression models for specific length were highly significant, with p-values less than 0.05 for most terms.

Expansion ratio

The expansion ratio is most strongly affected by die head temperature (C), with a positive coefficient (0.1487), indicating that higher temperatures lead to a greater expansion. Moisture content (A) has a negative effect (-0.0945), meaning higher moisture reduces the expansion ratio. Screw speed (B) has a smaller positive influence (0.0375), contributing to a slight increase in expansion. The interaction terms have minimal effects, with AB showing a slight positive effect (0.0238), while AC and BC have negligible impacts. The quadratic terms reveal that increasing moisture content beyond a certain point (A^2, -0.1261) decreases expansion, while higher screw speeds (B^2, 0.0861) can enhance the expansion ratio.

$$\text{Expansion ratio} = 2.86 - 0.0945 * A + 0.0375 * B + 0.1487 * C - 0.0238 * AB - 0.0012 * AC + 0.0188 * BC - 0.1261 * A^2 + 0.0861 * B^2 - 0.0306 * C^2 \quad (3)$$

The R^2 value of 0.9430 demonstrates that 94.30% of the variation in the expansion ratio is explained by the model, signifying a highly reliable fit. The adjusted R^2 of 0.8918 further corroborates that the model effectively fits the data. The predicted R^2 of 0.6954 shows reasonable predictive ability for expansion ratio optimization. The adequate precision of 16.3996 indicates a robust signal, suggesting the model is well-suited for navigating the design space. The F-value of 18.39 confirms that the model is statistically significant. The non-significant lack of fit ensures that the model adequately represents the data, while the C.V. of 2.52% reflects high precision and reliability for the expansion ratio measurements.

An increase in screw speed and die head temperature resulted in higher expansion ratios, as higher die head temperatures and screw speeds promoted the vaporization of water during the extrusion process, leading to greater puffing of the product (Altan *et al.*, 2008; Kamble and Pawar, 2018). Conversely, higher feed moisture content reduced expansion, likely due to increased dough viscosity, which hindered the expansion process (Ding *et al*., 2005 and Chocha *et al*., 2024).). The regression model showed a strong fit for expansion ratio, with R^2 values above 0.9, indicating the model's accuracy in predicting the response under various conditions.

Generally, as bulk density decreases due to higher die head temperatures and screw speeds, the specific length tends to increase, resulting in lighter, elongated products. Higher temperatures also enhance the expansion ratio but may negatively affect bulk density, indicating a need for careful balance in optimizing extrusion conditions. Moisture content shows a negative correlation with both expansion ratio and specific length, as increased moisture leads to higher densities and reduced expansion capability. Understanding these interrelations is crucial for fine-tuning extrusion processes.

Machine torque

The model reveals that machine torque is negatively affected by both feed moisture content (A) and die head temperature (B), with coefficients of -0.6124 and -1.17, respectively, indicating that higher values of these parameters require less torque due to reduced material viscosity. The screw speed (C) has a smaller negative influence (-0.0732). Interaction effects such as AB suggest that combined increases in moisture and temperature further reduce torque, while the quadratic term for moisture content (A^2, 1.32) implies that high moisture may eventually lead to increased torque, likely due to changes in the material's rheological properties.

$$\text{Machine torque} = 16.70 - 0.6124 * A - 1.17 * B - 0.0732 * C - 0.125 * AB - 0.125 * AC - 0.125 * BC + 1.32 * A^2 - 0.0865 * B^2 - 0.0903 * C^2 \tag{4}$$

The model shows a strong fit with an R^2 value of 0.8875, meaning 88.75% of the variance in machine torque is explained by the independent variables. The adjusted R^2 value of 0.7862 confirms a good model fit, while the predictive R^2 of 0.2611 suggests limitations in predictive capability. The adequate precision of 11.5074 indicates that the model is effective for navigating the design space and the F-value of 8.76 highlights its statistical significance. The lack of fit being non-significant (NS) further assures the model's reliability in representing the data, with a coefficient of variation (C.V.) of 4.54% reflecting precision in torque measurements.

Mass flow rate

The feed moisture content (A) has a positive effect (3.31), indicating that higher moisture levels increase the mass flow rate. However, die head temperature (B) has a slight negative effect (-0.1964), and screw speed (C) significantly reduces mass flow rate (-0.8820). The interaction terms show that the combination of high moisture and other parameters reduces flow rate, while the quadratic terms reveal that excessive moisture (A^2, -6.09) leads to decreased flow due to increased viscosity. Conversely, higher die head temperatures (B^2, 1.52) promote better flow, while screw speed (C^2, -2.02) negatively affects it.

$$\text{Mass flow rate} = 171.75 + 3.31 * A - 0.1964 * B - 0.8820 * C - 2.13 * AB - 3.13 * AC - 2.38 * BC - 6.09 * A^2 + 1.52 * B^2 - 2.02 * C^2 \tag{5}$$

The R^2 value of 0.8703 indicates that the model explains 87.03% of the variability in mass flow rate, with an adjusted R^2 of 0.7535 affirming the fit's validity. The predictive R^2 of 0.5837 suggests moderate predictive ability. Adequate precision of 10.2570 indicates effective model performance for optimization purposes. The F-value of 7.45 signifies statistical significance, and the non-significant lack of fit reassures the model's robustness, supported by a C.V. of 2.26%, underscoring the reliability of mass flow rate measurements.

In summary, while moisture content significantly enhances mass flow rate, it negatively impacts machine torque. High die head temperatures reduce torque but can positively influence mass flow, illustrating the complex interplay between these machine parameters during the extrusion process.

ANOVA Table and Regression Coefficients for Response Surface Quadratic Model

Regression analysis of the experimental data yielded empirical models that describe the effects of the independent variables on the physical parameters and machine parameters of the extrudates. The models demonstrated high coefficients of determination ($R^2 > 0.87$), indicating that the independent variables accounted for a significant proportion of the variability in the response variables.

ANOVA results as shown in Table 4, showed that the models were highly significant ($p < 0.001$) for all response variables, while the lack of fit test was non-significant ($p > 0.05$), indicating that the models adequately described the experimental data. The small coefficients of variation further confirmed the precision and reliability of the experimental results (Singh *et al.*, 2018; Dhingra *et al.*, 2012).

Conclusion

This study demonstrates the successful development of extruded snacks using a blend of pearl millet flour and defatted peanut flour through the application of Response Surface Modelling. The optimized processing parameters significantly affected the physical parameters of the extrudates, indicating their potential for high-quality snack production. The empirical models developed provided a strong fit with the experimental data, offering valuable insights into the effects of extrusion conditions on the physical and machine parameters of the extruded snacks. The findings suggest that blending these flours can enhance the nutritional profile of snacks while maintaining high standards of product quality.

The results of this study contribute to the growing body of research on the use of alternative flours in snack production, offering practical solutions for the development of healthier and more sustainable food products. Future research should focus on evaluating the sensory properties and consumer acceptance of these extruded snacks to further explore their potential in the market.

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