Process optimization of extrusion variables and effects on some quality and sensory characteristics of extruded snacks from whole pearl millet-based flour

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Abstract

This study investigated the effects and optimization of the respective feed compositions of pearl millet flour (PMf), African walnut flour (AWf), and corn starch (CS) [FC, (100:0:0, 90:5:5, and 80:10:10)], feed moisture content [FMC, (10, 15, and 20%)] and barrel temperature [BT, (60, 70, and 80 °C)] on some quality characteristics of extruded snacks using Box-Behnken design. The AWf and CS were substituted at 0, 5, and 10% in PMf and evenly mixed with sterile water to attain the required FMC. The resultant dough was processed in a twin-screw extruder into whole pearl millet-based snacks. The results showed that the extrusion variables significantly influenced ($p < 0.05$) the quality and extrudate properties examined. The good fits of the response models were affirmed favourably by the adequacy of the coefficient of determination (> 0.90), absolute average deviation (≤ 0.05), accuracy factor (≤ 1.05), and bias factor (≤ 1.01). The optimization of the combined interactive effects on an extruded snack prepared using 80% PMf, 10% AWf, and 10% CS cooked with 15% FMC at 60 °C BT gave desirable crude protein, fat, fibre contents with complementary low residence time, increased expansion ratio, and was liked moderately by the sensory panellists. Pearl millet-based snacks could be a worthy alternative to gluten-free snacks.

Article Highlights

1. The extrusion variables' interactive effect significantly influenced the pearl-millet snacks' quality changes.
2. High feed composition and lower feed moisture resulted in high protein, fibre, & fat.
3. The response models were affirmed favourably by the adequacy of the indices examined.

Keywords Pearl millet-based flours · Extrusion · Optimization · Quality characteristics · Gluten-free snacks

1 Introduction

Millet is an ancient grain and predominantly native grown crops in African and Asian regions of the world. Their promotion as a food source is profoundly related

to the presence of healthy components such as dietary fibre and phytochemical compounds [1]. The grains are deficient in gluten proteins, which makes them suitable for preparing a gluten-free diet. Millets exist as distantly related crop species. Among these groups, pearl millets

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(*Pennisetum glaucum*) serve as primary economic importance, generally used to prepare traditional staple foods in developing countries [1]. According to Onyeoziri et al. [2], the drawbacks of the industrial food use of whole-grain pearl millet flour are its unpleasant sensory characteristics and limited storage life. Therefore, there is a need to improve its food palatability and perishability through its intermediate product compositing with other food crops and an acceptable modern processing technique.

The use of composite flour presents an alternative means to improve food product quality. The edible seeds of African walnut (*Tetracarpidium conophorum*) have been reported to be rich in protein, minerals, essential fatty acids, and indispensable amino acids [3–5]. Despite this vital nutritional composition, the nut is underutilized and less studied as an intermediate product such as flour in food composites [4, 6]. Moreover, Fasogbon et al. [7] showed its significance as a low cost functional and nutrient-dense food by substituting walnut flour in wheat flour to prepare a cookie snack. Thus, the nut flour can be substituted in starchy staples to promote its final product use and contribute to food and nutrition security.

The rapid urbanizing communities in developing countries demand convenience-type products along with health-promoting effects and appealing sensory attributes. Accordingly, there is a great interest in food extrusion technology to manufacture ready-to-eat foods [8]. Food extrusion is a thermal and shear-based processing technique in a sealed barrel. Herein, food doughs are cooked through multifaceted unit operations under controlled variable conditions, and subsequently, pseudoplastic melt strand structures are forced through a fixed die at the barrel discharge. Several extrusion independent process variables, such as feed composition (FC), feed moisture (FM), and barrel temperature (BT), induce reactions that affect extrudate quality attributes [9, 10].

Yadav et al. [11] substituted whey protein concentrate (WPC) at 0–7.5% in pearl millet grits and used 14% FM to produce an expanded pearl millet-based snack. They reported that greater percentage incorporation of WPC resulted in a simultaneous increase of breaking strength, hardness, bulk density, nutritional composition, and decreased expansion ratio and the sensory score of the derived extrudates. Gulati et al. [12] and Jalgaonkar et al. [13] explored response surface methodology to investigate the effects of BT (50–150 °C), FM (17–35%), and screw speed (170–250 revolution per minute) on the quality properties of resultant millets expanded products. FM was consistently found to impact the antioxidant activity, bulk density, hardness, radial expansion ratio, cooking time, swelling and hydration capacities of the derived products [12, 13]. The authors rated the desirable products as those containing low moisture levels. Accordingly, FC and FM

are key process variables for the development of novel expanded millet products. The effects of other process variables on the quality characteristics of extrudates from pearl millet blended with other flour sources have been studied. Generally, legumes such as cowpea and groundnut have been incorporated in pearl millet flour to produce different extruded products [14, 15]. However, none of the previous studies has utilized African walnut flour to produce extruded snacks.

Food starches play a vital role in the extrusion cooking of snacks by improving consistent quality properties [16]. Corn starch is among several starches used in the extrusion processing to aid higher thermal stability. It enhances the production of extrudates with better structural characteristics [16]. This study investigates some quality and sensory characteristics of extruded snacks from whole pearl millet flour, African walnut flour, and corn starch. The optimization of the extrusion variables was also carried out using response surface methodology (RSM).

2 Materials and methods

2.1 Materials

Whole pearl millet grains (*Pennisetum glaucum*), African walnut (*Tetracarpidium conophorum*), and food-grade corn starch used for this study were purchased at a local market in Abeokuta (7.5 °N, 4.5 °E), Ogun State, Nigeria.

2.1.1 Processing of whole pearl millet-based flour

Pearl millet grains were inspected visually to remove debris and extraneous objects after sorting and winnowing. The recovered cleaned grains were milled (fabricated micro mill) and screened using 500 µm sieve fitted to a sieve shaker (Analysette 3 Spartan, Fritsch, Germany) to obtain whole-grain pearl millet flour. The method described by Fasogbon et al. [7] was slightly modified to process African walnut flour. The fresh African walnuts were washed thoroughly to remove adhering substance and boiled for two hours to detach the nutshells. The obtained nuts were cut into thin slices of 2 mm thickness and blanched for 5 min. Further to this, the blanched edible nuts were drained and oven-dried (NYC-101, FCD-3000 serials, Medical and Scientific, England, UK) at 60 °C for five hours. The dried slices were milled and sieved (500 µm) to obtain African walnut flour (AWf). The composite flour formulation was prepared by substituting AWf and corn starch (CS) at 0, 5, and 10% in pearl millet flour (PMf). The formulations were packaged separately in well-labelled Ziploc bags and stored at 4 °C before further use.

2.1.2 Experimental design and process optimization

Based on preliminary experimental data, varying levels of respective feed composition of PMf, AWf, and CS [FC, (100:0:0, 90:5:5, and 80:10:10)], feed moisture content [FMC, (10, 15, and 20%, w.b.)], and barrel temperature [BT, (60, 70, and 80 °C)] were established. A Box-Behnken experimental design generated via RSM with the independent variables was used to optimize the extrusion process (Minitab 18 Lt, Coventry, UK). Each variable's levels were established, resulting in 17 experimental runs (Table 1). The mathematical regression model illustrating the relationship between the dependent (responses) and independent variables in terms of their linear, quadratic, and interaction effects are described by the second-order polynomial model as shown in Eq. (1).

$$Y = \beta_0 + \beta_1 FC + \beta_2 FMC + \beta_3 BT + \beta_{11} FC^2 + \beta_{22} FMC^2 + \beta_{33} BT^2 + \beta_{12} FC * FMC + \beta_{13} FC * BT + \beta_{23} FMC * BT + \epsilon \quad (1)$$

Where; predicted response—Y, the equation regression coefficients: β_0 (intercept), β_1 – β_3 (linear effect), β_{11} – β_{33} (quadratic effect), and β_{12} – β_{23} (interaction effect).

2.1.3 Extrusion process of whole pearl millet-based snacks

The extrusion process was carried out using a fabricated laboratory-scale twin-screw extruder with the barrel

diameter (65.2 mm), nominal screw length (1898 mm), restriction die (3 mm), and power (5 hp) [17]. Other extruder's geometric details and design parameter values had been reported by Sobowale et al. [17]. The pearl millet-based snacks extrusion process was done as previously described by Kareem et al. [18] with slight modification. Briefly, 100 g of each feed composition (Table 1) was mixed with the dry ingredients (0.75% iodized salt and 7.5% sugar). To this, distilled water was intermittently added and preconditioned to the experimental designed levels of FMC (10–20% wb) to form doughs. The extruder operating conditions were pre-set at BT of 60–80 °C and a constant screw speed of 700 rpm (optimum value reported in our previous study, [19]). The extrudate properties were measured in-process. The resultant extrudate strands were immediately sliced at 2 mm thickness as they exited

from the die, cooled to 25 °C for 30 min, and then dried at 60 °C till the constant final moisture content was recorded. The extruded pearl-millet-based snacks were allowed to cool and divided into two batches. A batch was milled and examined for proximate composition, water and oil absorption capacities. The second batch was packaged in well-labelled Ziploc bags and subsequently evaluated for bulk density and sensory evaluation. The experimental

Table 1 Coded and real values for Box-Behnken design

Runs	Coded values			Real values		
	X ₁	X ₂	X ₃	FC (%)	FMC (%)	BT (°C)
1	0.00	1.00	−1.00	90:5:5	20	60
2	1.00	0.00	−1.00	80:10:10	15	60
3	−1.00	0.00	−1.00	100:0:0	15	60
4	0.00	0.00	0.00	90:5:5	15	70
5	1.00	1.00	0.00	80:10:10	20	70
6	0.00	−1.00	−1.00	90:5:5	10	60
7	0.00	−1.00	1.00	90:5:5	10	80
8	0.00	0.00	0.00	90:5:5	15	70
9	−1.00	1.00	0.00	100:0:0	20	70
10	−1.00	0.00	1.00	100:0:0	15	80
11	0.00	0.00	0.00	90:5:5	15	70
12	−1.00	−1.00	0.00	100:0:0	10	70
13	0.00	1.00	1.00	90:5:5	20	80
14	1.00	−1.00	0.00	80:10:10	10	70
15	0.00	0.00	0.00	90:5:5	15	70
16	1.00	0.00	1.00	80:10:10	15	80
17	0.00	0.00	0.00	90:5:5	15	70

X₁–Feed composition (%), X₂–Feed moisture content (%), X₃–Barrel temperature (°C), 100, 90, and 80% (PMf), and 0, 5, 10 (AWf and CS)

data obtained thereof were employed for the optimization of the extrusion process of the snacks.

2.2 Proximate analysis

The proximate composition of the extruded snacks; moisture (wb), crude protein, crude fat, crude fibre, ash, and total carbohydrate was determined respectively using the standard analytical procedure 934.01, 990.03, 920.39 (A), 978.10, 923.03 (32.1.05), and by difference [20].

2.3 Extrudates properties

2.3.1 Expansion ratio

The expansion ratio was determined by obtaining the ratio between the extrudate's cross-sectional diameter and the diameter of the extruder die opening [21]. The average expansion ratio of seven replicates of the samples was reported.

2.3.2 Mass flow rate (MFR)

The mass flow rate was determined when steady-state extrusion operation conditions were attained as indicated by constant torque at the different barrel temperatures [19]. A stopwatch was used to time the sample's entry until the extrudates flowed out of the extruder die orifice at 60 s intervals. The average mass of triplicate collections was recorded in kilogram per second.

2.3.3 Residence time

During extrusion, the residence time was expressed as the time taken in seconds for a red colour print to be visible at the die orifice [22]. Three determinations were reported as an average value.

2.4 Functional properties

2.4.1 Bulk density

The bulk density of the extrudates was determined using the procedure of Kareem et al. [18] by measuring the diameter d , (cm), length L , (cm), and mass m , (g) of the samples. The bulk density was expressed using the Equation below:

$$\text{Bulk density} = \frac{4m}{\pi d^2 L} \quad (2)$$

2.4.2 Water absorption capacity (WAC) and oil absorption capacity (OAC)

The methodology described by Garcia-Valle et al. [23] was used to determine the WAC and OAC of the pearl millet-based extrudates.

2.4.3 Sensory evaluation

For the sensory acceptability test, ethical clearance was granted for the study by the research ethics committee of Moshood Abiola Polytechnic, Abeokuta, Nigeria. The member panellists' informed consent ($n = 50$) used for this evaluation was sort and gotten. The judges were regular snack consumers and thus requested to assess each coded sample of the extruded snacks using a nine-point hedonic scale where 1—dislike very much and 9—like extremely. The snacks were evaluated for aroma, colour, crispness, taste, appearance, and overall acceptability. The judges were provided with water to rinse their mouths before and after each testing.

2.5 Statistical analysis

The triplicate determinations and multiple replications of experimental data obtained were subjected to analysis of variance (ANOVA) using SPSS version 22 (New York, USA). The average determinations were presented as mean and standard deviation with significant F tests at $p < 0.05$ probability levels. The statistical models were generated using Minitab 18 software and used to execute ANOVA on the models at a 5% confidence level. The terms that were not significant were deleted from the model equations. Validation of the model equations generated was done using Eqs. (3–5) to estimate the absolute average deviation (AAD), accuracy factor (A_f), and bias factor (B_f). Comparison of the experimental and predicted values was made using the calculated coefficient of determination (R^2).

$$\text{AAD} = \frac{\left[\sum_{i=1}^N \left(\frac{Y_{i,\text{exp}} - Y_{i,\text{cal}}}{Y_{i,\text{exp}}} \right) \right]}{N} \quad (3)$$

$$B_f = 10^{\frac{1}{N} \sum_{i=1}^N \log \left(\frac{Y_{i,\text{cal}}}{Y_{i,\text{exp}}} \right)} \quad (4)$$

$$A_f = 10^{\frac{1}{N} \sum_{i=1}^N \left| \log \left(\frac{Y_{i,\text{cal}}}{Y_{i,\text{exp}}} \right) \right|} \quad (5)$$

where; number of experiments— N , calculated response— $Y_{i,cal}$, experimental response— $Y_{i,exp}$.

3 Result and discussion

The average proximate composition of pearl millet and African walnut flours is reported in Table 2 (published data from other authors). The proximate composition of pearl millet-based extruded snacks as influenced by FC, FMC, and BT is presented in Table 3. The moisture, crude protein, crude fibre, crude fat, ash, and carbohydrate content ranged from 8.81–12.25%, 5.89–13.28%, 2.05–2.82%, 3.06–9.41%, 2.11–2.78%, and 60.63–73.58%, respectively. The bulk density, WAC, OAC, MFR, residence time, and expansion ratio of the pearl millet-based extrudates varied from 0.41–0.59 g/cm³, 5.34–8.10 mL/g, 5.06–6.96 mL/g, 2.22–2.63 kg/s, 15.50–28.00 s, and 4.53–6.82, respectively (Table 4). Table 5 depicts the regression coefficient and R^2 , AAD, Af, and Bf values for the mathematical models of the responses evaluated in this study. The sensory properties of pearl millet-based extruded snacks are shown in Table 6. The mean scores for colour, taste, aroma, appearance, crispness, and overall acceptability varied from 4.30–6.90, 3.90–6.85, 4.15–7.60, 3.10–8.80, 3.75–6.75, and 3.85–7.05, respectively. Figure 1 shows the responses' surface plots (proximate composition, functional and extrudates properties) evaluated.

3.1 Proximate composition of pearl millet-based extruded snacks

The proximate composition of the extruded snacks showed varying significant differences ($p < 0.05$). The moisture content of the pearl millet-based snacks was $< 12.5\%$. This percentage level is a quality index indicating that the product will be less susceptible to spoilage microbes' deterioration effect and, thus, have long shelf stability [18, 19]. The least crude protein content was noted for 100% pearl millet snacks. Snacks containing 80% pearl millet flour, 10% Awf, and 10% corn starch gave the highest protein content. The increasing blending flour ratio of Awf in pearl millet snacks could have resulted in the highest crude protein content. The surface plot (Fig. 1B) reflected a similar

observation. Tonfack Djikeng et al. [5] reported that African walnut seeds are a rich source of protein (24.18%). Besides, nut crops have been found to increase snacks' protein content as established with cashew nut composite extrudates [26]. The increasing level of the protein content of the pearl millet-based extruded snacks is therefore expected. On the other hand, Dahlin and Lorenz [27] highlighted that lower BT ($< 180^\circ\text{C}$) and FMC (15%) might induce a protective effect by increasing product viscosity during the extrusion process, which in turn reduced the reaction rate of degradative processes such as Maillard reaction. Accordingly, the regression coefficient (Table 5) showed that only the positive quadratic effect of FMC (X_2^2) had a significant ($p < 0.05$) effect on the extruded snacks' ash content. Furthermore, the surface plot (Fig. 1E) of the ash content of snacks reflects mineral elements presence and displayed higher value with an increase in BT and decreased FC. These effects were consistent with the result obtained for extruded cocoyam noodles by Sobowale et al. [19]. Therefore, the higher BT reduced moisture content during extrusion cooking and concentrated the available inorganic matter [28].

The extruded snacks' crude fat content was profoundly high in samples with the highest substitution level of Awf. Interestingly, fat serves as an extrusion processing aid by impacting the lubricating effect in the feed composition and equally influencing the snacks' palatability. The increase in fat content relative to the blending ratio could be attributed to the high-fat level (46.5%) in Awf [3]. The fat content of the pearl-millet based extrudates falls within the range (1.75–15.09%) reported for high-quality cassava and tiger nut extruded snacks [18], while the level (4.4–4.7%) reported for extruded pearl millet-based supplementary foods [14] could be comparable to some of the snacks. The reduction effect when high BT was applied could be two-fold either related to the change in the state of the fat to oil, which enhanced the removal of oil from the system, or oxidation effect of unsaturated fatty acids, which changes to lipid hydroperoxides, as such lowering the fat content of the extrudates [29]. The response surface plot displayed the changes in fat content as FC and BT functions (Fig. 1D). Nonetheless, the regression model of fat content revealed significant ($p < 0.05$) effects with the positive linear effect of BT (X_3) and the quadratic effect of FMC (X_2^2).

Table 2 Average values of proximate composition for pearl millet and African walnut flours (published data from other authors) Sources Adebiji et al. [24], Obadina et al. [25], Fasogbon et al. [7], Tonfack Djikeng et al. [5]

Control sample	Moisture (%)	Protein (%)	Fat (%)	Fibre (%)	Ash (%)	Carbohydrate (%)
Pearl millet flour	11.63	6.93	4.65	1.16	1.77	74.00
African walnut flour	3.55	24.22	50.61	14.85	5.69	8.88

Table 3 Proximate composition of pearl millet-based extruded snacks

Variables		Moisture (%)		Crude protein (%)		Crude fibre (%)		Crude fat (%)		Ash (%)		Carbohydrate (%)	
		Exp	Pred	Exp	Pred	Exp	Pred	Exp	Pred	Exp	Pred	Exp	Pred
X ₁ (%)	X ₂ (%)	X ₃ (°C)											
90:5:5	20	60	8.98 ^b (0.02)	8.69	10.24 ^{ab} (0.03)	11.50	2.14 ^a (0.01)	2.08	3.06 ^a (0.05)	1.53	2.16 ^{ab} (0.01)	2.35	73.31 ^j (0.10)
80:10:10	15	60	9.41 ^c (0.06)	9.24	11.61 ^b (0.06)	10.10	2.27 ^{de} (0.01)	2.10	3.20 ^a (0.06)	2.81	2.27 ^{bc} (0.04)	2.09	70.98 ^h (0.63)
100:0:0	15	60	9.71 ^d (0.06)	9.98	10.83 ^{ab} (0.01)	9.96	2.07 ^{ab} (0.04)	2.06	3.65 ^b (0.16)	4.25	2.44 ^{de} (0.03)	2.37	71.58 ⁱ (0.49)
90:5:5	15	70	8.81 ^a (0.02)	8.81	10.21 ^{ab} (0.02)	10.21	2.23 ^{de} (0.04)	2.23	3.08 ^a (0.03)	3.08	2.11 ^a (0.02)	2.11	73.58 ^j (0.08)
80:10:10	20	70	10.64 ^f (0.06)	11.10	11.48 ^b (0.04)	11.73	2.09 ^{ab} (0.05)	2.32	4.28 ^c (0.03)	6.20	2.29 ^c (0.07)	2.28	69.24 ^f (0.15)
90:5:5	10	60	10.40 ^e (0.06)	10.60	11.04 ^{ab} (0.02)	12.16	2.19 ^{cd} (0.01)	2.43	4.48 ^d (0.12)	5.80	2.47 ^{de} (0.04)	2.54	69.39 ^f (0.20)
90:5:5	10	80	10.91 ^h (0.06)	11.20	11.89 ^b (0.69)	10.63	2.36 ^{fg} (0.01)	2.42	4.74 ^e (0.06)	6.27	2.66 ^f (0.01)	2.47	66.96 ^d (0.15)
90:5:5	15	70	8.81 ^a (0.02)	8.81	10.21 ^{ab} (0.02)	10.21	2.23 ^{de} (0.04)	2.23	3.08 ^a (0.03)	3.08	2.11 ^a (0.02)	2.11	73.58 ^j (0.08)
100:0:0	20	70	10.76 ^g (0.03)	10.78	12.24 ^b (0.01)	11.85	2.28 ^{ef} (0.04)	2.35	4.57 ^d (0.04)	5.50	2.55 ^e (0.07)	2.44	67.62 ^e (0.02)
100:0:0	15	80	10.50 ^e (0.09)	10.67	5.89 ^a (7.71)	7.40	2.05 ^a (0.04)	2.22	4.17 ^c (0.05)	4.56	2.17 ^{ab} (0.05)	2.35	69.84 ^g (0.22)
90:5:5	15	70	8.81 ^a (0.02)	8.81	10.21 ^{ab} (0.02)	10.21	2.23 ^{de} (0.04)	2.23	3.08 ^a (0.03)	3.08	2.11 ^a (0.02)	2.11	73.58 ^j (0.08)
100:0:0	10	70	12.25 ⁱ (0.01)	11.79	10.03 ^{ab} (0.01)	9.78	2.52 ^h (0.04)	2.29	8.86 ^g (0.01)	6.94	2.37 ^c (0.01)	2.38	63.98 ^c (0.08)
90:5:5	20	80	11.55 ⁱ (0.04)	11.35	12.51 ^b (0.01)	11.40	2.82 ^j (0.08)	2.58	8.14 ^f (0.03)	6.82	2.78 ^g (0.04)	2.71	62.21 ^b (0.18)
80:10:10	10	70	11.88 ^j (0.03)	11.86	13.28 ^b (0.03)	13.68	2.65 ^j (0.00)	2.58	9.41 ^h (0.06)	8.48	2.18 ^{ab} (0.02)	2.29	60.63 ^a (0.06)
90:5:5	15	70	8.81 ^a (0.02)	8.81	10.21 ^{ab} (0.02)	10.21	2.23 ^{de} (0.04)	2.23	3.08 ^a (0.03)	3.08	2.11 ^a (0.02)	2.11	73.58 ^j (0.08)
80:10:10	15	80	12.07 ^k (0.07)	11.80	10.16 ^{ab} (0.06)	11.03	2.43 ^g (0.02)	2.44	8.83 ^g (0.04)	8.24	2.32 ^c (0.11)	2.40	64.20 ^c (0.25)
90:5:5	15	70	8.81 ^a (0.02)	8.81	10.21 ^{ab} (0.02)	10.21	2.23 ^{de} (0.04)	2.23	3.08 ^a (0.03)	3.08	2.11 ^a (0.02)	2.11	73.58 ^j (0.08)

Means with different superscripts within a column are significantly different ($p < 0.05$). Values in parenthesis are the standard deviations of the respective averages. X₁–Feed composition, X₂–Feed moisture content, X₃–Barrel temperature, Exp–Experiment value, Pred–Predicted value

Table 4 Extrudates and functional properties of pearl millet-based extruded snacks

Variables	Bulk density (g/cm ³)			Water absorption capacity (mL/g)		Oil absorption capacity (mL/g)		Mass flow rate (kg/s)		Residence time (s)		Expansion ratio		
	X ₁ (%)	X ₂ (%)	X ₃ (°C)	Exp	Pred	Exp	Pred	Exp	Pred	Exp	Pred	Exp	Pred	
90:5:5	20	60	0.59 ^j (0.00)	0.59	6.15 ^c (0.04)	7.15	6.02 ^d (0.01)	6.62	2.63 ^e (0.01)	2.56	19.50 ^e (0.71)	18.81	5.34 ^c (0.03)	5.79
80:10:10	15	60	0.57 ^h (0.01)	0.58	6.31 ^c (0.04)	6.67	6.06 ^{de} (0.01)	6.23	2.46 ^c (0.02)	2.51	16.50 ^{ab} (0.71)	15.37	6.23 ^{de} (0.02)	6.15
100:0:0	15	60	0.55 ^g (0.02)	0.51	6.44 ^d (0.03)	6.18	6.12 ^e (0.00)	5.92	2.42 ^c (0.01)	2.46	18.00 ^{bcd} (0.00)	18.75	6.33 ^e (0.01)	5.88
90:5:5	15	70	0.52 ^{def} (0.01)	0.52	6.12 ^c (0.02)	6.12	6.09 ^e (0.01)	6.09	2.43 ^c (0.03)	2.43	24.50 ^f (0.71)	24.50	4.66 ^{ab} (0.03)	4.66
80:10:10	20	70	0.52 ^{ef} (0.01)	0.51	7.70 ^f (0.20)	6.35	6.41 ^f (0.01)	5.64	2.56 ^d (0.01)	2.58	24.00 ^f (0.00)	25.81	5.81 ^d (0.01)	5.44
90:5:5	10	60	0.50 ^{de} (0.00)	0.54	7.94 ^g (0.03)	6.84	6.55 ^g (0.04)	5.98	2.25 ^a (0.02)	2.22	15.50 ^a (0.71)	16.56	6.13 ^{de} (0.01)	6.21
90:5:5	10	80	0.46 ^c (0.01)	0.46	8.06 ^g (0.01)	7.06	6.96 ^h (0.02)	6.36	2.23 ^a (0.03)	2.30	17.50 ^{bcd} (0.71)	18.19	6.82 ^f (0.03)	6.37
90:5:5	15	70	0.52 ^{def} (0.01)	0.52	6.12 ^c (0.02)	6.12	6.09 ^e (0.01)	6.09	2.43 ^c (0.03)	2.43	24.50 ^f (0.71)	24.50	4.66 ^{ab} (0.03)	4.66
100:0:0	20	70	0.41 ^a (0.01)	0.46	8.10 ^g (0.02)	7.36	6.93 ^h (0.01)	6.53	2.46 ^c (0.01)	2.48	19.00 ^{de} (0.00)	18.94	4.53 ^a (0.01)	4.53
100:0:0	15	80	0.44 ^b (0.01)	0.43	7.44 ^e (0.19)	7.08	6.45 ^f (0.04)	6.28	2.59 ^{de} (0.01)	2.54	15.50 ^a (0.71)	16.63	5.94 ^{de} (0.03)	6.02
90:5:5	15	70	0.52 ^{def} (0.01)	0.52	6.12 ^c (0.02)	6.12	6.09 ^e (0.01)	6.09	2.43 ^c (0.03)	2.43	24.50 ^f (0.71)	24.50	4.66 ^{ab} (0.03)	4.66
100:0:0	10	70	0.43 ^b (0.00)	0.44	5.49 ^{ab} (0.16)	6.85	5.06 ^a (0.05)	5.83	2.37 ^b (0.01)	2.35	28.00 ^g (1.41)	26.19	6.03 ^{de} (0.02)	6.40
90:5:5	20	80	0.50 ^d (0.01)	0.46	5.66 ^b (0.02)	6.76	5.25 ^b (0.04)	5.82	2.44 ^c (0.02)	2.47	18.50 ^{cde} (0.71)	17.44	5.22 ^c (0.03)	5.13
80:10:10	10	70	0.53 ^{fg} (0.00)	0.48	6.11 ^c (0.02)	6.85	5.83 ^c (0.04)	6.23	2.22 ^a (0.03)	2.20	17.00 ^{abc} (1.41)	17.06	5.23 ^c (0.02)	5.23
90:5:5	15	70	0.52 ^{def} (0.01)	0.52	6.12 ^c (0.02)	6.12	6.09 ^e (0.01)	6.09	2.43 ^c (0.03)	2.43	24.50 ^f (0.71)	24.50	4.66 ^{ab} (0.03)	4.66
80:10:10	15	80	0.42 ^{ab} (0.00)	0.46	5.34 ^a (0.08)	5.60	5.26 ^b (0.01)	5.46	2.47 ^c (0.02)	2.43	18.50 ^{cde} (0.71)	17.75	5.04 ^{bc} (0.74)	5.49
90:5:5	15	70	0.52 ^{def} (0.01)	0.52	6.12 ^c (0.02)	6.12	6.09 ^e (0.01)	6.09	2.43 ^c (0.03)	2.43	24.50 ^f (0.71)	24.50	4.66 ^{ab} (0.03)	4.66

Means with different superscripts within a column are significantly different ($p < .05$). Values in parenthesis are the standard deviations of the respective averages. X₁–Feed composition, X₂–Feed moisture content, X₃–Barrel temperature, Ex–Experiment value, Pred–Predicted value

Table 5 Coefficient of regression, R^2 , AAD, A_f , and B_f values for the mathematical models of the responses

Coefficient	Moisture	Protein	Fat	Ash	CHO	BD	MFR	RT	Expansion ratio
α_0	8.810	10.210	3.080	2.1100	73.580	0.5200	2.4300	24.500	4.660
α_1	0.098	0.943	0.559	−0.0587	−0.996	0.0262	−0.0162	−0.563	−0.065
α_2	−0.439*	0.029	−0.930	0.0125	1.428	0.0125	0.1275*	0.375	−0.414*
α_3	0.816	−0.409	1.436*	0.0737	−2.756*	−0.0487*	−0.0037	0.063	−0.126
α_{11}	1.267*	−0.125	1.779	0.0100	−3.515*	−0.0325	0.0350	−1.563	0.374
α_{22}	1.305	1.673*	1.921*	0.2275*	−4.698*	−0.0150	−0.0625	−0.938	0.366
α_{33}	0.345	−0.463	0.104	0.1800	−0.915	0.0075	0.0200	−5.812*	0.851*
α_{12}	0.063	−1.003	−0.210	−0.0175	1.242	0.0025	0.0625	4.000*	0.520*
α_{13}	0.468	0.872	1.277	0.0800	−1.260	−0.0100	−0.0400	1.125	−0.200
α_{23}	0.515*	0.355	1.205	0.1075	−2.168	−0.0125	−0.0425	−0.750	−0.203
R^2	0.97	0.93	0.97	0.95	0.91	0.94	0.98	0.95	0.95
AAD	0.02	0.05	0.01	0.03	0.01	0.04	0.01	0.03	0.03
A_f	1.02	1.05	1.01	1.03	1.01	1.04	1.01	1.03	1.03
B_f	1.00	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00

CHO: carbohydrate; BD: bulk density; WAC: water absorption capacity; OAC: oil absorption capacity; MFR: mass flow rate; RT: retention time; ER: expansion ratio. α_0 , α_1 – α_3 , α_{11} – α_{33} , and α_{12} – α_{23} are the equation regression coefficients for intercept, linear, quadratic, and interaction coefficient, respectively, R^2 : coefficient of determination, AAD: average absolute deviation, A_f : accuracy factor, B_f : bias factor. *Significant at $p < .05$

Table 6 Sensory properties of pearl millet-based extruded snacks

X_1 (%)	X_2 (%)	X_3 (°C)	Colour	Taste	Aroma	Appearance	Crispness	Overall acceptability
90:5:5	20	60	6.90	6.85	7.60	7.37	6.75	7.05
80:10:10	15	60	5.95	6.60	6.40	6.95	6.75	7.00
100:0:0	15	60	5.25	6.25	7.35	6.20	5.95	6.25
90:5:5	15	70	5.25	5.40	6.10	6.05	6.35	5.30
80:10:10	20	70	4.30	6.45	5.60	4.10	4.25	4.65
90:5:5	10	60	5.80	5.10	6.00	5.95	4.80	5.00
90:5:5	10	80	4.30	4.50	5.50	3.10	3.90	4.15
90:5:5	15	70	5.25	5.40	6.10	6.05	6.35	5.30
100:0:0	20	70	4.45	4.95	5.50	4.45	3.75	3.85
100:0:0	15	80	4.35	4.75	4.15	4.70	3.85	3.85
90:5:5	15	70	5.25	5.40	6.10	6.05	6.35	5.30
100:0:0	10	70	5.45	6.05	5.45	6.70	5.90	6.00
90:5:5	20	80	6.50	4.90	5.20	7.85	5.40	6.20
80:10:10	10	70	4.40	4.15	4.35	8.80	4.45	4.20
90:5:5	15	70	5.25	5.40	6.10	6.05	6.35	5.30
80:10:10	15	80	5.10	3.90	6.40	6.10	5.55	5.40
90:5:5	15	70	5.25	5.40	6.10	6.05	6.35	5.30

X_1 –Feed composition, X_2 –Feed moisture content, X_3 –Barrel temperature

Dietary fibres are an essential food component that promotes varying beneficial physiological effects in the human system. Previous studies have reported the fibre content in pearl millet flour, 1.06% d.b. [25], AWf, 2.60% d.b. [3], and corn starch, 0.90 g [30]. Therefore, it appeared that the crude fibre content of the snacks increased with the inclusion level of AWf. In

addition to the inclusion level of AWf, fibre molecules present in flour samples are subject to change during extrusion cooking [31]. Thus, slight differences in the snacks' fibre content due to the extrusion cooking may be related to BT's effect, as shown on the surface plot (Fig. 1C). This observation is in line with the submission of Singh et al. [9] that mild extrusion condition (lower

Fig. 1 Surface plots of the responses (proximate composition, extrudates, and functional properties) evaluated. **A** Moisture **B** Crude protein **C** Crude fibre **D** Crude fat **E** Ash **F** Carbohydrate **G**

Bulk density **H** Water absorption capacity **I** Oil absorption capacity **J** Mass flow rate **K** Residence time **L** Expansion ratio

temperature < 200 °C, low residence time, or high moisture content) is associated with a less significant effect on dietary fibre content but could aid in the redistribution of some fibre fractions.

Pearl millet, among other cereals, is a primary starch source, the main complex carbohydrate molecule. As expected, the extrudates' carbohydrate content was generally high, mainly due to the higher proportion of pearl millet flour. The range observed is comparable and higher than the carbohydrate content (61.30–65.20%) of extruded pearl millet-based supplementary foods [14]. Accordingly, the estimated carbohydrate model showed significant ($p < 0.05$) effects relative to the negative linear effect of BT (X_3) and the quadratic effect of FC and FMC (X_2^1 and X_2^2 , respectively). The surface plot (Fig. 1F) further depicted decreases in the extrudates' carbohydrate content with concomitant reductions in FMC and BT. These observations are in accordance with the study of cornmeal extrusion by Wen et al. [32] and Politz et al. [33]. They reported that lower FMC (12.5–20%), BT (140–180 °C), and increase in screw speed (100–500 rpm) significantly reduced high molecular weight polysaccharide (amylopectin) in the extruded products. These variable effects could be made possible considering that gelatinization during extrusion cooking occurs at lower FMC (12–22%), resulting in easy fragmentation by shearing effects on the amylopectin component's branched nature starch [9].

3.2 Functional properties of pearl millet-based extruded snacks

Alam et al. [10] stated that functional properties are quality indices that play a critical role in extruded foods' acceptability. The bulk density of the pearl millet-based extrudates is an important attribute due to its impact on container fill, and it is associated with expansion level during extrusion. Therefore, the bulk density and expansion ratio of extrudates are inversely related. For instance, an increase in one parameter is proportional to the other's decrease [21]. The extrudates and functional properties of the pearl millet-based extruded snacks (Table 4) showed a similar sequence. The increase in extrudate bulk density was due to the rise in FC with the corresponding decrease in FMC. The samples' expansion ratio decreased with a simultaneous reduction in FC and increased FMC. Pearl millet-whey protein concentrate extrudates showed a related expansion ratio range (4.34–5.47) [11]. The enhanced bulk density and proportional reduction in the samples' expansion ratio may be due to the high fibre and protein content in the extrudates containing AWf. Table 2 also reference the high protein and fibre levels in AWf. Fibre components like non-starch polysaccharides and protein globulins type retain moisture firmly during extrusion, which may restrain moisture loss at the exit die [11, 21]. Thus, the extrudates showed decreases in the expansion ratio and increased bulk density values. Similar trends were also depicted

on the respective parameters' surface plots (Figs. 1G and 1L). Further to this, the estimated regression coefficient (Table 5) indicated that the negative linear effect of BT (X_3) had a significant ($p < 0.05$) effect on bulk density while the negative linear effect of FMC (X_2), the positive quadratic effect of BT (X_3^2) and interaction effect between FC and FMC (X_1X_2) showed significant ($p < 0.05$) effect on the expansion ratio. Several studies have also demonstrated that FC and FMC had significant effects on the expansion ratio of food extrudates [11, 16].

The knowledge of water absorption capacity is critical to explain and predict extruded food products' behavioural changes. The WAC of the pearl millet-based extrudates revealed that the snacks prepared with 100% PMf, 20% FMC, and extruded at 70 °C BT gave the maximum value (8.10 mL/g) while 10% substitution level of AWf and corn starch, 15% FMC and cooked at 70 °C had the least WAC (5.34 mL/g). The higher WAC of the 100% pearl millet snacks suggested the availability of larger starch fragments [28]. Regarding the WAC surface plot (Fig. 1H), a concomitant decrease in FC and FMC increase displayed higher WAC. FMC influence on the extrudates' WAC is per with other studies [12, 34]. Oil absorption capacity (OAC) is concerned with the structural entrapment of oil in food products. The OAC increased with the rise in substitution level of FC and decrease in FMC (Fig. 1I). As earlier discussed, the high level of oil in AWf might have influenced higher OAC. The high absorption rate could be attributed to the disorientation of starch molecules during extrusion, which liberated partial release of amylose chains prone to form complexes with lipids [23, 35]. Moreover, the WAC and OAC regression models presented no significant ($p < 0.05$) linear, quadratic, and interaction effects; nonetheless, the parameter's surface plots described sufficient trends.

3.3 Extrudates properties of pearl millet-based extruded snacks

The mass flow rate (MFR) explains the resistant flow generated by the rotating screw and the pressure developed due to the restriction of the exit die in a twin-screw extruder [36]. The extruded snacks' MFR revealed less significant differences ($p < 0.05$) within samples, and the value increased with an increase in FMC. The MFR regression coefficient was also significantly ($p < 0.05$) influenced by FMC positive linear effect. This observation agrees with Sobowale et al. [22]. They varied FMC between 30 and 40% and reported that the mass flow rate of wheat-plantain noodles increased at constant FMC. According to Anuonye et al. [37], the residence time is a function of FMC, BT, screw geometry, among other related factors. The residence time of the extruded snacks revealed decreases in value with

the increasing rate of incorporated flour blends. This effect could be that the resultant matrix was less dense and took less time to pass through the opening die. Furthermore, the residence time of the snacks indicated a significant ($p < 0.05$) effect with respect to the negative quadratic effect of BT (X_3^2) and positive interactive effect of FC and FMC (X_1X_2). Pictorial representation of the responses displayed a simultaneous decrease and increased FC and FMC, respectively. The observed trends reflected increased MFR and residence time of the extruded snacks (Figs. 1J and 1K).

The effects of feed variables (FC and FMC) and BT on the responses (proximate composition, functional and extrudates properties) studied, and their varying mathematical regression models are presented in Table 5. The estimated coefficient of determination (R^2) revealed that all model responses were greater than 0.90 (Table 5). The R^2 values observed in this study were closely related to that (> 0.95) reported by Sobowale et al. [19], thus indicating the response models' validity and good consonance between the predicted and experimental data. Previous co-authors have also attributed a good fit of data to R^2 value > 0.90 to measure the adequacy of models illustrating the studied quality attributes [38]. Other adequacy indices estimated, including AAD, are determined by values close to zero, whereas A_f and B_f are assessed based on values nearness to one. Thus, the computed values of these parameters further validated the response models with acceptable conformity.

3.4 Sensory properties of pearl millet-based extruded snacks

Sensory tests of pearl millet-based snacks also represent a measure of its food quality.

Onyeoziri et al. [2] reported that the extrusion cooking of whole-grain pearl millet flour enhanced the resulting porridge's sensory characteristics (in terms of cereal-like aromas and flavour). As such, the food extrusion of the grain flour-based mix could improve the desirable sensory profile of the obtained extrudates. In this study, the extruded snacks' sensory properties showed significant differences ($p < 0.05$) between experimentally designed samples (Table 6). These changes observed in the evaluated parameters may be directly proportional to the modification induced by the optimized variables' different combination effects (FC, FMC, and BT). For instance, the least score for aroma, colour, crispness, taste, and appearance of the extruded snacks may be due to the mild browning reaction, gelatinization/breakdown of starch molecules, or relative interactions within these modifications at elevated temperature and pressures in conjunction with the in-barrel shearing effect during extrusion [18, 39]. With respect

to the overall acceptability scores, the panellists moderately liked the extrudates prepared from 80% PMf, 10% AWf, and 10% corn starch containing 15% FMC at 60 °C BT while 100% pearl millet extrudates with respective 15 and 20% FMC at 70 and 80 °C BT rated same least score and disliked moderately.

4 Conclusion

This study demonstrated that the interactive effects induced between FC, FMC, and BT on the proximate composition, functional and extrudates properties, and sensory characteristics of the pearl millet-based extruded snacks examined were significantly influenced ($p < 0.05$) by the extrusion variables. The high level of AWf and lower FMC influenced better crude protein, fat, and fibre content, while the rise in BT showed higher ash content of the snacks. On the other hand, the enhanced bulk density, WAC, OAC, MFR, and proportional reduction in the expansion ratio and residence time of the extrudates were significantly ($p < 0.05$) dependent on either the increase or decrease of FC and FMC. The R^2 (> 0.90), AAD (≤ 0.05), A_f (≤ 1.05), and B_f (≤ 1.01) confirmed the adequacy of the indices employed and thus describe a good correlation of the experimental data to the predicted data. This study also revealed that the optimization of the combined effects of extrusion variables on the extruded snacks prepared using 80% Pearl millet flour, 10% African walnut flour, and 10% corn starch cooked with 15% FMC at 60 °C BT was liked moderately by the sensory panellists and gave desirable quality snacks. Thus, the pearl millet-based extruded snacks could be a worthy alternative to gluten-free snacks.

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Declarations

Conflict of interest The author(s) declared no conflicts of interest exist in the submitted manuscript, and all authors approve it for publication.

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