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Optimization and Validation of Extrusion Process Parameters for the Sensory Characteristics of Extruded Aerial Yam and Soybean Flour Blends

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Abstract - **The aim of this study was to optimize and validate the extrusion process parameters (barrel temperature, screw speed, and feed moisture) for the sensory properties (texture, taste, appearance, and aroma) of extrudates made from blends of soybean and aerial yam flours. Five levels of barrel temperature (95, 100, 105, 110, and 115 °C), screw speed (85, 100, 115, 130, and 145 rpm), and feed moisture (31, 33, 35, 37, and 39%) were employed in 20 runs of the response surface methodology (RSM), which was based on the Box-Behnken design with three variables. A single-screw extruder at the laboratory scale was used to carry out the extrusion procedure. A high regression coefficient ($R^2 \geq 0.9$) indicates that the models are useful for navigating the design space. Numerical optimization results indicated that the optimal extrusion process parameters - barrel temperature of 114.12 °C, screw speed of 100.56 rpm, and feed moisture of 38.02% - produced extrudates with optimal sensory property scores of 5.34 for texture, 4.91 for taste, 6.97 for appearance, and 5.80 for aroma, with a desirability of 0.943. The correlation between the predicted and experimental values yielded a high coefficient of determination, indicating a good correlation. The "Fit and Diagnostic Case" statistics showed a low range of deviations between the predicted and observed values for the sensory characteristics. Therefore, the generated quadratic model accurately predicts the sensory characteristics of aerial yam-soybean flour blends and is thus validated.**
Keywords: **Extrusion, Optimization, Sensory Properties, Response Surface Methodology, Aerial Yam-Soybean Blends**

I. INTRODUCTION

One of the most significant characteristics of food or dietary materials is their sensory qualities, which include the food's color, texture, flavor, aroma, and appearance. These qualities are crucial as they ensure product quality, assess demand, and present food in an enticing and fresh manner for consumption. Food quality is frequently assessed using sensory characteristics - such as the appearance, flavor, texture, aroma, and taste of foods - that can be detected by human senses.

Aerial yam (Dioscorea bulbifera) is one of the lesser-known varieties of sweet potato, producing bulbils that resemble potatoes rather than traditional sweet potatoes, earning it the nickname "flying/air potatoes." It is cultivated in Southeast Asia, West Africa, and South and Central America. For various reasons, including its general obscurity and a notably more severe delayed flavor sensation compared to other sweet potato species, it is rarely consumed and typically neglected at both household and industrial levels. Nevertheless, Dioscorea bulbifera has significant application potential and could be utilized in the development of new industrial products, as well as for its economic relevance [12].

Soybean (Glycine max), a major oilseed belonging to the Leguminosae family, is typically grown for food. To increase the variety of extruded food products, make them more affordable, and enhance their nutritional content, wheat flour can be substituted with soybean flour up to 25% [12].

Extrusion is primarily a thermo-mechanical manufacturing process that incorporates several unit operations, such as mixing, kneading, shearing, conveying, heating, cooling, shaping, partial drying, or puffing, depending on the materials and machinery employed [13].

Extrusion cooking, also known as the high-temperature/short-time (HTST) interaction, is an important and well-known food processing technique used to produce fiber-rich foods. This interaction combines moisture, pressure, temperature, and mechanical shear to plasticize and cook damp, starchy, and proteinaceous food components in a cylinder, resulting in molecular changes and chemical reactions [11].

The optimization process is essential in formulating and developing acceptable food products from neglected food crops, as well as in controlling process conditions or variables to produce extrudates with the desired quality [10].

The experimental data are assessed using response surface methodology (RSM) to develop a statistical model (linear, quadratic, cubic, or two-factor interaction [2FI]). The model's coefficients are expressed using constant terms, linear coefficients for independent variables A, B, and C, interactive term coefficients AB, AC, and BC, and quadratic term coefficients A^2, B^2, and C^2. The adequacy of the model is assessed using the correlation coefficient (R^2), adjusted determination coefficient (Adj-R^2), and appropriate precision. A model is considered adequate when its p-value is less than 0.05, its "lack of fit" p-value is greater than 0.05, R^2 is greater than 0.9, and its adjusted precision is greater than 4. Analysis of variance can be used to determine the statistical significance of mean differences [3].

RSM is frequently used in the production of extruded food products and aids in optimizing various process operational variables [8]-[14]. The most popular factorial designs used in the creation of food products are Central Composite Design (CCD) and Box-Behnken Design (BBD), which estimate the response surface and then optimize the process variables. In recent years, optimization studies have also utilized Face Central Composite Design (FCCD) and Central Composite Rotatable Design (CCRD).

Despite its growing use in food processing, extrusion remains a complex process that requires optimization and validation for specific applications, depending on the type of raw ingredients and the intended final product. Minor differences in processing parameters can significantly impact process variables and product quality, even within a specific extrusion process [4].

This study aims to optimize and validate the extrusion process parameters (barrel temperature, screw speed, and feed moisture) for the sensory properties (texture, taste, appearance, and aroma) of extrudates made from blends of soybean and aerial yam flour.

II. MATERIALS AND METHODS

A. Procurement of Soybean Seeds and Aerial Yam Bulbs

The soybean seeds and aerial yam bulbs used in this study were obtained from the Uyo Urban Market in the Uyo Local Government Area, Akwa Ibom State, Nigeria.

B. Flour Sample Preparation

Flour samples used in this study were prepared according to standard methods in the Crop Processing Laboratory of the Department of Agricultural Engineering at Akwa Ibom State University, Ikot Akpaden, Akwa Ibom State, Nigeria.

1. Preparation of Aerial Yam Flour

This was accomplished using the procedure outlined in [10]. After cleaning and sifting to remove extraneous materials, the aerial yam bulbs were cut into 10 mm-thick slices and peeled. The slices were then washed with clean water. Subsequently, the slices (chips) were dried in an oven set to 60 °C for 12 hours. Following drying, the slices (chips) were milled using an Italian-made MF120 Hammer Mill and passed through a laboratory sieve with a 600 µm aperture. The resulting flour was collected and stored for later use in a polyethylene bag.

2.Preparation of Soybean Flour

The preparation process outlined in [12] was followed. Splits and damaged beans were removed from the seeds through screening. The seeds were then washed and rolled for 30 minutes at 100 °C. After being oven-dried for 12 hours at 70 °C, the seeds were ground in a disc attrition mill. A 100-mesh standard sieve was used to sift the milled full-fat soybean flour. The flour was subsequently stored at room temperature in an airtight polyethylene bag for later use.

3. Preparation of Sample Blends

A blend of aerial yam flour and soybean flour was prepared using a ratio of 25:75, consisting of 25% aerial yam flour and 75% soybean flour.

C. Extrusion Process

The extrusion process was conducted using a single-screw laboratory-scale extruder, as described in [13]. Two hundred grams (200 g) of the flour blend was accurately measured and preconditioned to the desired moisture levels, as indicated in the experimental design layout (Table II). The extruder was turned on, and the screw speeds and barrel temperatures were adjusted according to the experimental design (Table II). The raw material was fed into the extruder via a hopper. Upon exiting the die, the extrudates were collected, dried in an oven, and sealed in airtight plastic bags for further laboratory examination.

D. Determination of Sensory Characteristics

The sensory quality attributes of the extruded aerial yam-soybean flour blends were determined using a 9-point hedonic scale, ranging from 1 (extremely dislike) to 5 (neither like nor dislike) to 9 (extremely like) [7]. A ten-member, semi-trained panel evaluated the samples and scored them based on the texture, taste, appearance, and aroma of the extrudates.

E. Design of Experiment and Analysis of Data

The experimental design and layout utilized Design Expert (version 11.0.1), a statistical software application. Three independent parameters were employed in the experiment: barrel temperature (X_1), screw speed (X_2), and feed moisture levels (X_3). Five levels of each parameter were used in the Central Composite Randomized Design (CCRD) are shown in Table I. The coded values for the independent variables were -2, -1, 0, 1, and 2, where -2 represents the lowest level, 0 represents the medium (midpoint), and 2 represents the highest level, respectively as shown in Table I.

TABLE I CODED AND ACTUAL VALUES OF DIFFERENT EXPERIMENTAL VARIABLES

Factors	Units	Codes	Levels					Interval of Variation
			-2	-1	0	1	2	
Barrel temp.	℃	X_1	95	100	105	110	115	5.0
Screw speed	rpm	X_2	85	100	115	130	145	15.0
Feed moisture	%	X_3	31	33	35	37	39	2.0

TABLE II EXPERIMENTAL LAYOUT FOR 3 VARIABLES AND 5 LEVELS RESPONSE SURFACE EXPERIMENTAL DESIGN FOR THE EXTRUSION OF AERIAL YAM AND SOYBEAN FLOUR

Runs Order	Coded Factors			Actual Factors		
	X_1	X_2	X_3	BT (^{O}C)	SS (rpm)	FM (%)
1	0.000	0.000	-2.000	105.00	115.00	31.00
2	0.000	0.000	0.000	105.00	115.00	35.00
3	0.000	0.000	0.000	105.00	115.00	35.00
4	0.000	-2.000	0.000	105.00	85.00	35.00
5	-1.000	1.000	-1.000	100.00	130.00	33.00
6	1.000	-1.000	1.000	110.00	100.00	37.00
7	-1.000	-1.000	1.000	100.00	100.00	37.00
8	1.000	1.000	-1.000	110.00	130.00	33.00
9	0.000	0.000	0.000	105.00	115.00	35.00
10	2.000	0.000	0.000	115.00	115.00	35.00
11	-2.000	0.000	0.000	95.00	115.00	35.00
12	0.000	0.000	2.000	105.00	115.00	39.00
13	0.000	0.000	0.000	105.00	115.00	35.00
14	-1.000	-1.000	-1.000	100.00	100.00	33.00
15	1.000	1.000	1.000	110.00	130.00	37.00
16	1.000	-1.000	-1.000	110.00	100.00	33.00
17	0.000	2.000	0.000	105.00	145.00	35.00
18	-1.000	1.000	1.000	100.00	130.00	37.00
19	0.000	0.000	0.000	105.00	115.00	35.00
20	0.000	0.000	0.000	105.00	115.00	35.00

Note: BT = Barrel temperature, SS = Screw speed, FM = Feed moisture

Table II displays the independent variables, coded variables, uncoded variables, and their respective coded and uncoded levels. The empirical expression for the responses is represented in equation 1 as:

$$Y = \beta_0 + \sum_{i=1}^{2} \beta_i X_i + \sum_{i=1}^{2} \beta_{ii} X_i^2 + \sum_{i=1}^{2} \sum_{j=i+1}^{2} \beta_{ij} X_i X_j \quad (1)$$

Where Y = Response, β_0 = Constant term, $\sum_{i=1}^{2} \beta_i$ = Summation of coefficient of linear terms, $\sum_{i=1}^{2} \beta_{ii}$ = summation of quadratic terms, $\sum_{i=1}^{2} \sum_{j=i+1}^{2} \beta_{ij}$ = summation of coefficient of interaction terms, and $X_i X_j$ = independent variables

F. Model Selection for Optimization and Validation of Extrusion Process Parameters

Design Expert (version 11.0.1), a statistical software package for experimental design, was used to analyze and generate model equations for the responses (sensory characteristics).

In selecting a suitable model for the extrusion process parameters of the responses, the highest-order polynomial was considered, maximizing the predicted and adjusted correlation coefficients (Predicted R^2 and Adjusted R^2), ensuring that the additional terms are significant and that the model is not aliased. Consideration was also given to achieving a higher coefficient of determination (R^2) and lower standard deviation values [3].

The optimization of the extrusion process parameters (barrel temperature, screw speed, and feed moisture) was carried out using numerical methods in Response Surface Methodology (RSM), with the goals of maximizing barrel temperature and screw speed while determining the possible range for feed moisture.

To optimize the extrusion process parameters using numerical methods, which find a point that maximizes the desirability function, equal importance of 3 was assigned to all three extrusion process parameters and the responses. The main criteria and desired goals for each process parameter and the responses for sensory characteristics are presented in Table III.

TABLE III CRITERIA FOR NUMERICAL OPTIMIZATION OF EXTRUSION PROCESS PARAMETERS FOR SENSORY CHARACTERISTICS

Extrusion Criteria	Unit	Lower limit	Upper limit	Optimization Goal	Relative Importance
Barrel Temperature	℃	95.00	115.00	Maximize	3
Screw Speed	rpm	85.00	145.00	Maximize	3
Feed Moisture	%	31.00	39.00	Range	3
Texture		4.38	6.02	Range	3
Taste		4.68	6.78	Range	3
Appearance		4.58	6.97	Range	3
Aroma		4.45	7.00	Range	3

III. RESULTS AND DISCUSSION

A. Sensory Characteristics of Extruded Aerial Yam and Soybean Flour Blends

The results of the sensory characteristics (texture, taste, appearance, and aroma) of the extruded aerial yam-soybean flour blends are presented in Table IV.

TABLE IV SENSORY CHARACTERISTICS OF EXTRUDED AERIAL YAM AND SOYBEAN FLOUR BLENDS.

Sl. No.	BT (°C)	SS (rpm)	FM (%)	Texture	Taste	Appearance	Aroma
1	105	115	31	5.72±0.021	5.66±0.003	6.11±0.003	6.30±0.034
2	105	115	35	5.91±0.042	6.73±0.004	6.85±0.001	6.95±0.111
3	105	115	35	5.96±0.042	6.78±0.004	6.81±0.001	6.90±0.111
4	105	85	35	4.79±0.003	5.13±0.003	5.15±0.001	6.00±0.001
5	100	130	33	5.79±0.124	6.35±0.011	6.97±0.033	6.00±0.421
6	110	100	37	5.55±0.004	5.86±0.005	6.86±0.011	7.00±0.011
7	100	100	37	5.88±0.014	6.67±0.122	6.44±0.022	6.30±0.004
8	110	130	33	5.86±0.002	5.98±0.002	6.05±0.002	5.90±0.006
9	105	115	35	5.90±0.042	6.72±0.004	6.86±0.001	6.83±0.111
10	115	115	35	4.98±0.007	4.90±0.002	5.71±0.044	5.00±0.021
11	95	115	35	5.57±0.011	5.11±0.002	4.58±0.002	4.45±0.011
12	105	115	39	5.89±0.044	6.58±0.005	6.60±0.004	6.20±0.001
13	105	115	35	5.95±0.042	6.74±0.004	6.88±0.001	6.89±0.111
14	100	100	33	5.47±0.004	4.88±0.001	5.02±0.022	4.76±0.006
15	110	130	37	6.02±0.001	5.21±0.003	5.77±0.231	5.01±0.001
16	110	100	33	4.38±0.004	5.19±0.011	5.14±0.011	6.01±0.312
17	105	145	35	4.89±0.002	4.68±0.006	4.99±0.009	5.02±0.006
18	100	130	37	5.10±0.004	6.00±0.003	5.36±0.034	5.85±0.001
19	105	115	35	5.93±0.042	6.70±0.004	6.83±0.001	6.93±0.111
20	105	115	35	5.99±0.042	6.72±0.004	6.84±0.001	6.91±0.111

Note:Values are mean ± standard deviation of triplicate determination. BT=Barrel temperature, SS= Screw speed, FM= Feed moisture

1. Texture

The recorded scores for texture varied between 4.38 and 6.02 are shown in Table IV. This range of values is higher than the 1.96 to 4.64 observed for sorghum-based extruded products supplemented with defatted soy meal flour, as reported by Tadesse *et al.,* (2019), but lower than the 7.22 to 8.44 recorded for pulse-based snacks [2]. The highest score for texture (6.02) was recorded for the extrudate produced at a barrel temperature of 110 °C, a screw speed of 130 rpm, and a feed moisture of 37%, while the lowest score of 4.38 was recorded for the extrudate produced at a barrel temperature of 110 °C, a screw speed of 100 rpm, and a feed moisture of 33%.

2. Taste

For taste, the recorded scores ranged from 4.68 to 6.78 as shown in Table IV, which is relatively comparable to the 5.3 to 7.6 range for root and tuber composite flour noodles [1] and the 5.44 to 6.58 range for selected aerial yam cultivars and African breadfruit extruded snacks [5]. The highest score of 6.78 was obtained from the extrudate produced at a barrel temperature of 105 °C, a screw speed of 115 rpm, and a feed moisture of 35%, while the lowest score of 4.68 was obtained from the extrudate produced at a barrel temperature of 105 °C, a screw speed of 145 rpm, and a feed moisture of 35%.

3. Appearance

In Table IV, the recorded scores for the appearance of the extrudates ranged from 4.58 to 6.97. This range falls within the range of 2.96 to 6.68 for sorghum-based extruded products supplemented with defatted soy meal flour, as reported in [9], but is lower than the 6.89 to 8.22 range for pulse-based snacks [2]. The highest score of 6.97 for appearance was obtained from the extrudate produced at a barrel temperature of 100 °C, a screw speed of 130 rpm, and a feed moisture of 33%, while the lowest score of 4.58 was recorded for the extrudate produced at a barrel temperature of 95 °C, a screw speed of 115 rpm, and a feed moisture of 35%.

4. Aroma

The recorded scores for aroma are shown in Table IV. The results indicate that the values ranged from 4.45 to 7.00. This range is higher than the 4.88 to 6.80 range for sorghum-based extruded products supplemented with defatted soy meal flour, as reported in [9]. However, it is comparable to the 5.3 to 7.4 range for root and tuber composite flour noodles, as reported in [1]. Extrudates produced at a barrel temperature of 110 °C, a screw speed of 100 rpm, and 37% feed moisture had the highest score of 7.00, while extrudates produced at a barrel temperature of 95 °C, a screw speed of 115 rpm, and 35% feed moisture had the lowest score of 4.45 for aroma.

TABLE V COEFFICIENT OF REGRESSION/ANOVA FOR SENSORY CHARACTERISTICS

	Texture		**Taste**		**Appearance**		**Aroma**	
	Coeff.	**p-values**	**Coeff.**	**p-values**	**Coeff.**	**p-values**	**Coeff.**	**p-values**
X_O	-3.99		-396.48		-273.25		-482.80	
Linear								
X_1	0.1786	0.0142	4.34	0.0286	3.01	0.0356	5.71	0.0051
X_2	0.1703	0.0111	1.097	0.9618	1.36	0.7031	1.37	0.0003
X_3	-0.5336	0.0285	6.39	0.0029	2.33	0.0397	6.28	0.0541
Interaction								
X_1X_2	0.00402	< 0.0001	-0.00110	0.2783	-0.00175	0.1465	-0.00482	< 0.0001
X_1X_3	0.0201	0.0019	-0.0193	0.0233	0.0204	0.0346	-0.0161	0.0116
X_2X_3	-0.00879	0.0003	-0.0149	< 0.0001	-0.0210	< 0.0001	-0.0149	< 0.0001
Quadratic								
${X_1}^2$	-0.00650	0.0001	-0.0169	< 0.0001	-0.0166	< 0.0001	-0.0217	< 0.0001
${X_2}^2$	-0.00121	< 0.0001	-0.00199	< 0.0001	-0.00193	< 0.0001	-0.00154	< 0.0001
${X_3}^2$	-0.00750	0.2943	-0.0365	0.0049	-0.0284	0.0363	-0.0406	0.0003
Test for Model Adequacy								
R^2	0.9585		0.9630		0.9551		0.9831	
Pred. R^2	0.6617		0.7013		0.6424		0.8634	
Model F-value	25.65		28.92		23.62		64.68	
Lack of fit	31.98		111.45		183.53		24.77	

Note: X_o = intercept, X_1 = Barrel temperature, X_2 = Screw speed, X_3 = Feed moisture. Significance at $p < 0.005$

The results of the regression analysis and analysis of variance (ANOVA) for the optimization and validation of the extrusion process parameters affecting the sensory characteristics of extruded aerial yam and soybean flour blends are presented in Table V.

B. Model Selection/Equation for Optimization of Extrusion Process Parameters

1. Model Selection for Texture: Considering the model with the lowest standard deviation (0.1359) and the highest coefficients of determination, R^2 (0.9585), adjusted R^2 (0.9211), and predicted R^2 (0.6617), the quadratic model was selected for optimizing the extrusion process parameters for texture. The final regression model for texture is given in Equation 2 as follows:

$$T_X = -3.99 + 0.1786BT + 0.1703SS - 0.5336FM + 0.00402BTSS + 0.0201BTFM - 0.00879SSFM - 0.00650BT^2 - 0.00121SS^2 - 0.00750FM^2 \quad (2)$$

Where: T_X = Texture, BT = Barrel temperature (^{0}C), SS= Screw speed, FM= Feed moisture

In Equation (2), the positive terms signify a direct relationship between the extrusion process parameters and their interactions with the response (texture), while the negative terms indicate an inverse relationship. Two of the three extrusion process parameters - barrel temperature (BT) and screw speed (SS) - along with their interactions (BT × SS and BT × FM), exhibit a direct relationship with the response (texture). This implies that texture increases as barrel temperature, screw speed, and the interaction terms BT × SS and BT × FM increase. The quadratic terms (SS^2 and FM^2) demonstrate an inverse relationship with the response (texture).

The results of the regression analysis/ANOVA for the optimization of the extrusion process parameters affecting the sensory qualities of aerial yam and soybean flour blends reveal a model F-value of 25.65 for texture as shown in Table V, indicating that the model is significant. With the exception of FM^2, which has a p-value of 0.2943 - exceeding the 0.0500 level of significance - all other model variables are significant (Table V).

The texture "lack of fit" F-value of 31.98 suggests that the "lack of fit" is not statistically significant relative to the pure error. A "lack of fit" F-value this large could arise due to noise, with a mere 0.08% probability. Since a significant "lack of fit" is undesirable, this model is considered suitable for navigating the design space.

The model demonstrates significance, with a satisfactory coefficient of determination (R^2 = 0.9585) (Table V). This high R^2 value indicates a strong correlation between the independent variables (barrel temperature, screw speed, and feed moisture) and the response, suggesting that the texture model is adequate and can explain 95% of the total variability in the response.

2. Model Selection for Taste

Taking into consideration the model with the lowest standard deviation (0.2035) and the highest coefficient of determination, R^2 (0.9630), along with the adjusted R^2 (0.9297) and predicted R^2 (0.7013), the quadratic model was selected for the optimization of extrusion process parameters for taste. The final regression model for taste is given in Equation (3) as follows:

$$T_A = -396.48 + 4.34BT + 6.39FM - 0.00110BTSS - 0.0193BTFM - 0.0149SSFM - 0.0169BT^2 - 0.00199SS^2 - 0.0365FM^2 \quad (3)$$

where: T_A = Taste, BT= Barrel temperature (^{0}C), SS= Screw speed, FM= Feed moisture

In Equation (3), the positive terms signify a direct relationship between the extrusion process parameters and their interactions with the response (taste), while the negative terms indicate an inverse relationship. In this case, all three extrusion process parameters - barrel temperature (BT), screw speed (SS), and feed moisture (FM) - have a direct relationship with the response (taste). This implies that the response (taste) increases with an increase in all three extrusion process parameters.

The model is likely significant based on its F-value of 28.92 (Table V). When the "prob > F" values are less than 0.0500, it is assumed that the model terms are important. With the exception of SS and BT × SS, which have p-values of 0.9618 and 0.2783, respectively, all other model terms in this instance are significant (Table V).

The "Lack of fit" F-value of 111.45 for taste indicates that the "Lack of fit" is not statistically significant in relation to the pure error. Since fitting the model is the goal, a non-significant "Lack of fit" is favorable. As a result, this model can be used to navigate the design space. With an acceptable coefficient of determination, R^2 of 0.9630, the model proved significant (Table V).

The response (taste) and the independent variables (barrel temperature, screw speed, and feed moisture) exhibit a strong association, as evidenced by the high coefficient of determination. This suggests that the response model is adequate and accounts for 96% of the total variability in the response.

3. Model Selection for Appearance

The comparison of the four models (linear, two-factor interaction [2FI], quadratic, and cubic) for appearance in the extrusion of aerial yam-soybean flour blends indicated that the quadratic model was the best. Considering the model with the highest coefficient of determination, R^2 (0.9551), and predicted R^2 (0.6424), the quadratic model was selected for the optimization of extrusion process parameters for appearance (Table V). The final regression model for appearance is given in Equation (4) as follows:

$$A_p = -273.25 + 3.01BT + 2.33FM + 0.0204BTFM - 0.0210SSFM - 0.0166BT^2 - 0.00193SS^2 - 0.0284FM^2 \quad (4)$$

Where: A_P = Appearance, BT = Barrel temperature (^{o}C), SS= Screw speed, FM= Feed moisture

In Equation (4), the positive terms signify a direct relationship between the extrusion process parameters and their interactions with the response (appearance), while the negative terms indicate an inverse relationship. It was observed that two extrusion process parameters - barrel temperature (BT) and feed moisture (FM) - exhibit a direct relationship with the response, whereas their interactions, specifically BT × FM and screw speed × feed moisture (SS × FM), along with the quadratic terms (SS^2 and FM^2), demonstrate an inverse relationship with the response (appearance).

The model F-value for appearance, as shown in Table V, is 23.61, suggesting that the model is significant. When the "prob > F" values are less than 0.0500, it is assumed that the model terms are important. With the exception of screw speed (SS) and the interaction term BT × SS, which have p-values of 0.7031 and 0.1465, respectively, all of the model terms in this instance are significant (Table V).

The model's "lack of fit" F-value of 187.53 indicates that there is minimal "lack of fit" compared to the pure error. A significant "lack of fit" is undesirable since the goal is to achieve a good model fit. This implies that this method can effectively navigate the design space.

With an acceptable coefficient of determination, R^2 of 0.9551, the model proved significant (Table V). Excellent correlation was found between the response and the independent variables (feed moisture, screw speed, and barrel temperature), as indicated by the high coefficient of determination. This suggests that the response model is adequate and accounts for 95% of the response's overall variability.

4. Model Selection for Aroma

Taking into consideration the model with the lowest standard deviation (0.1479) and the highest coefficients of determination, R^2 (0.9831), adjusted R^2 (0.9679), and predicted R^2 (0.8634), the quadratic model was selected for the optimization of extrusion process parameters for aroma. The final regression model for aroma is given in Equation (5) as follows.

$$A_M = -482.80 + 5.71BT + 1.37SS - 0.00482BTSS - 0.0161BTFM - 0.0149SSFM - 0.0217BT^2 - 0.00154SS^2 - 0.0406FM^2 \quad (5)$$

where: A_M = Aroma, BT = Barrel temperature (^{0}C), SS= Screw speed, FM= Feed moisture

The positive terms in Equation (5) represent a direct relationship, while the negative terms represent an inverse relationship between the extrusion process parameters and their interactions with the response. The response (aroma) is directly correlated with barrel temperature (BT) and screw speed (SS), while their interactions - BT × SS, BT × FM, and SS × FM - along with the quadratic terms (SS^2 and FM^2), exhibit an inverse relationship with the response (aroma). The model is significant, as indicated by the model F-value of 64.68 for aroma in Table V. When "prob > F" values are less than 0.0500, the model terms are considered important. With the exception of feed moisture (FM), all of the model terms had significant p-values, with FM having a p-value of 0.0541.

According to the model's "Lack of Fit" F-value of 24.77, the "Lack of Fit" is not significant in comparison to the pure error. A non-significant "Lack of Fit" is favorable, as fitting the model is the goal. Therefore, this model can be used to navigate the design space.

With an acceptable coefficient of determination, R^2 of 0.9831, the model proved to be significant (Table V). An excellent correlation was found between the response and the independent variables (feed moisture, screw speed, and barrel temperature), as indicated by the high coefficient of determination. This suggests that the response quadratic model, which accounts for 98% of the response's overall variability, is sufficient.

C. Numerical Optimization and Validation of Extrusion Process Parameters

The main criteria for optimizing the constraints of the extrusion process parameters for sensory characteristics were the maximum possible barrel temperature and screw speed, as well as the specified range for feed moisture. The desired optimization goals and outputs for each extrusion process parameter and response are presented in Table VI.

TABLE VI OUTPUT FOR NUMERICAL OPTIMIZATION OF EXTRUSION PROCESS PARAMETERS FOR SENSORY CHARACTERISTICS

Extrusion Criteria	Unit	Lower limit	Upper Limit	Optimization Goal	Relative Importance	Output
Barrel Temperature	℃	95.00	115.00	Maximize	3	114.12
Screw Speed	rpm	85.00	145.00	Maximize	3	100.56
Feed Moisture	%	31.00	39.00	Range	3	38.02
Texture		4.38	6.02	Range	3	5.34
Taste		4.68	6.78	Range	3	4.91
Appearance		4.58	6.97	Range	3	6.97
Aroma		4.45	7.00	Range	3	5.80
Desirability						0.943

The optimal extrusion process parameters obtained were 114.12 °C for barrel temperature, 100.56 rpm for screw speed, and 38.02% for feed moisture. The optimum sensory characteristic scores were 5.34 for texture, 4.91 for taste, 6.97 for appearance, and 5.80 for aroma, with a desirability of 0.943 as shown in Table VI. Desirability is a utility function ranging from zero (not acceptable) to one (ideal), enabling the simultaneous optimization of multiple responses using numerical techniques [6]. To validate the sensory qualities, Table VI presents the optimal extrusion process parameters along with the best predicted responses.

TABLE VII OPTIMAL EXTRUSION PROCESS PARAMETERS WITH OPTIMUM PREDICTED RESPONSE FOR VALIDATION OF THE SENSORY CHARACTERISTICS

Extrusion Process Parameters				**Optimum Predicted Responses**			**Measured Responses**				**Desirability**
BT	**SS**	**FM**	**TX**	**TA**	**AP**	**AM**	**TX**	**TA**	**AP**	**AM**	
114.12	100.56	38.02	5.34	4.91	6.97	5.80	5.31	4.97	6.84	5.86	0.943

Note: BT = Barrel Temperature, SS = Screw Speed, FM = Feed Moisture, TX = Texture, TA = Taste, AP = Appearance, AM = Aroma

To validate the quadratic model for the response (sensory characteristics: texture, taste, appearance, and aroma), a test run was conducted under the optimal extrusion process parameters of 114.12 °C for barrel temperature, 100.56 rpm for screw speed, and 38.02% for feed moisture. The experimental (measured) values obtained were 5.31 for texture, 4.97 for taste, 6.84 for appearance, and 5.86 for aroma (Table VII). A strong correlation was observed between the experimental (measured) and predicted values for the responses (texture, taste, appearance, and aroma) when comparing the results for the optimal responses.

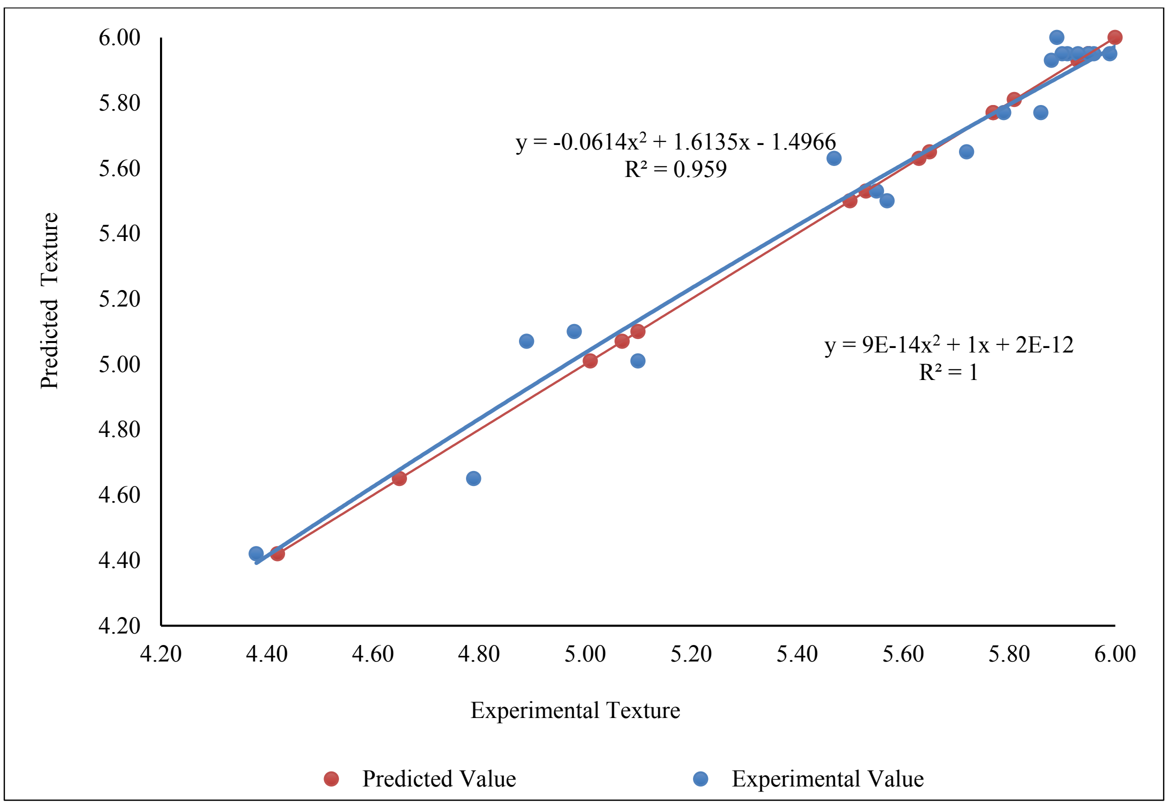

Fig. 1 Comparison of the predicted and experimental values for Texture

A comparison of the experimental and predicted values for texture is presented in Fig. 1. The data points were observed to be approximately aligned in a straight line, indicating close proximity to each other. The correlation between the predicted and experimental values yielded a coefficient of determination R^2 value of 0.959. This high coefficient of determination indicates a strong correlation. The deviation between the predicted and experimental values (residuals) was low, ranging from -0.04 to 0.20. Therefore, the generated quadratic model demonstrates accuracy in predicting the texture of the aerial yam-soybean flour blend.

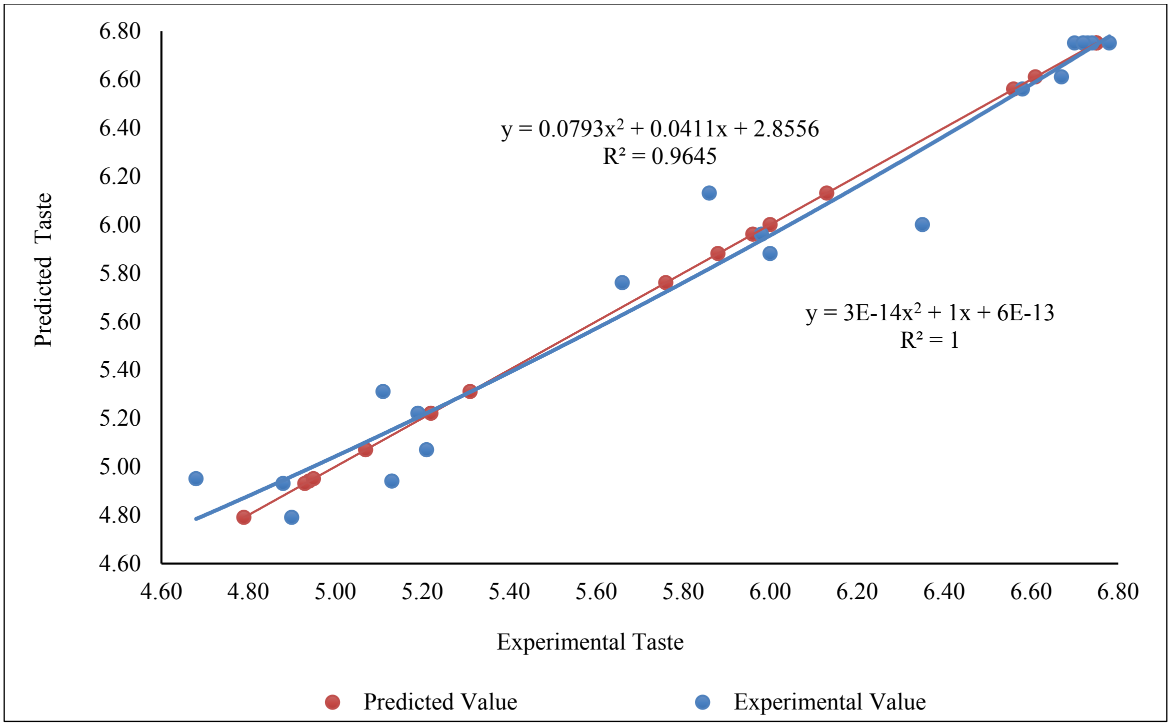

Fig. 2 Comparison of the predicted and experimental values for Taste

A comparison of the experimental and predicted values for taste is presented in Fig. 2. The data points were observed to be approximately aligned in a straight line. The correlation between the predicted and experimental values yielded a coefficient of determination R^2 value of 0.964. This high coefficient of determination indicates a good correlation. The deviation between the predicted and experimental values (residuals) ranged from -0.005 to 0.353, which is quite low. Therefore, the generated quadratic model demonstrates accuracy in predicting the taste of the aerial yam-soybean flour blend and is thus validated.

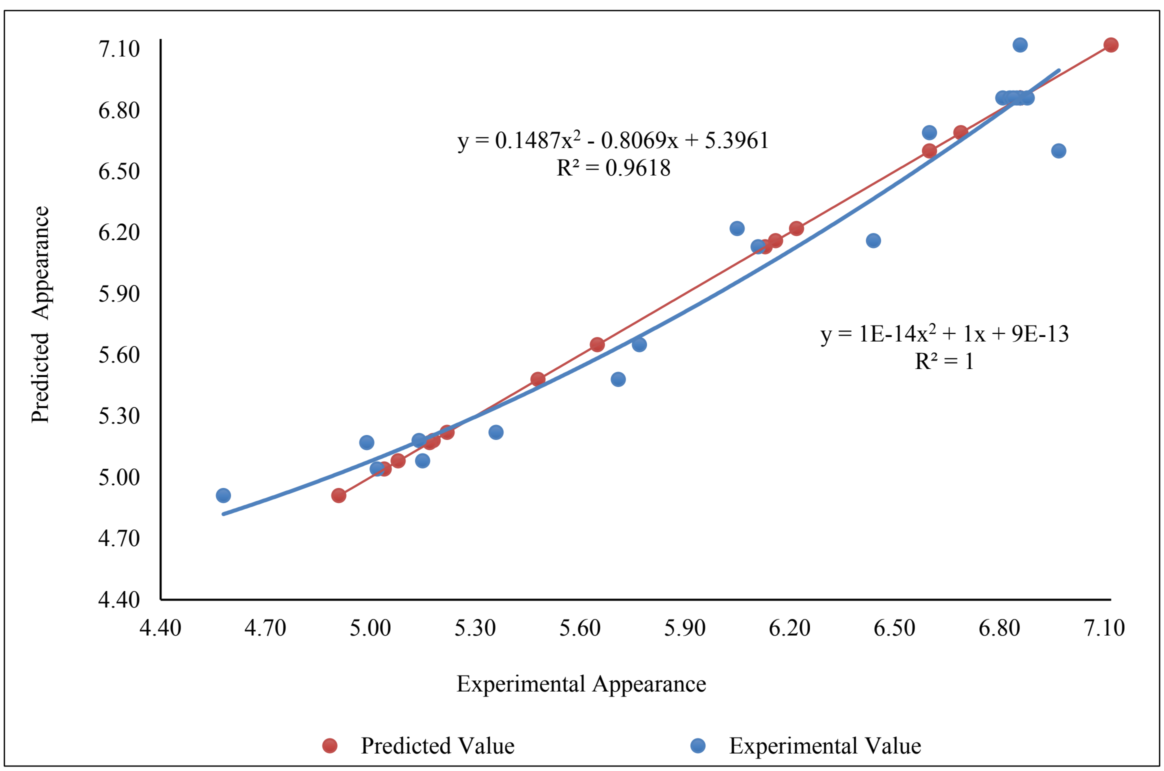

Fig. 3 Comparison of the predicted and experimental values for Appearance

A comparison between the experimental and predicted values for appearance is shown in Fig. 3. From the plot, the data points were observed to be approximately aligned in a straight line. The correlation between the predicted and experimental values yielded a coefficient of determination R^2 value of 0.961. This high coefficient of determination indicates a strong correlation. The 'Fit and Diagnostic Case' statistics showed that the deviation between the predicted and experimental values (residuals) for appearance is low, ranging from -0.002 to 0.225. Therefore, the generated quadratic model demonstrates accuracy in predicting the appearance of aerial yam-soybean flour blends.

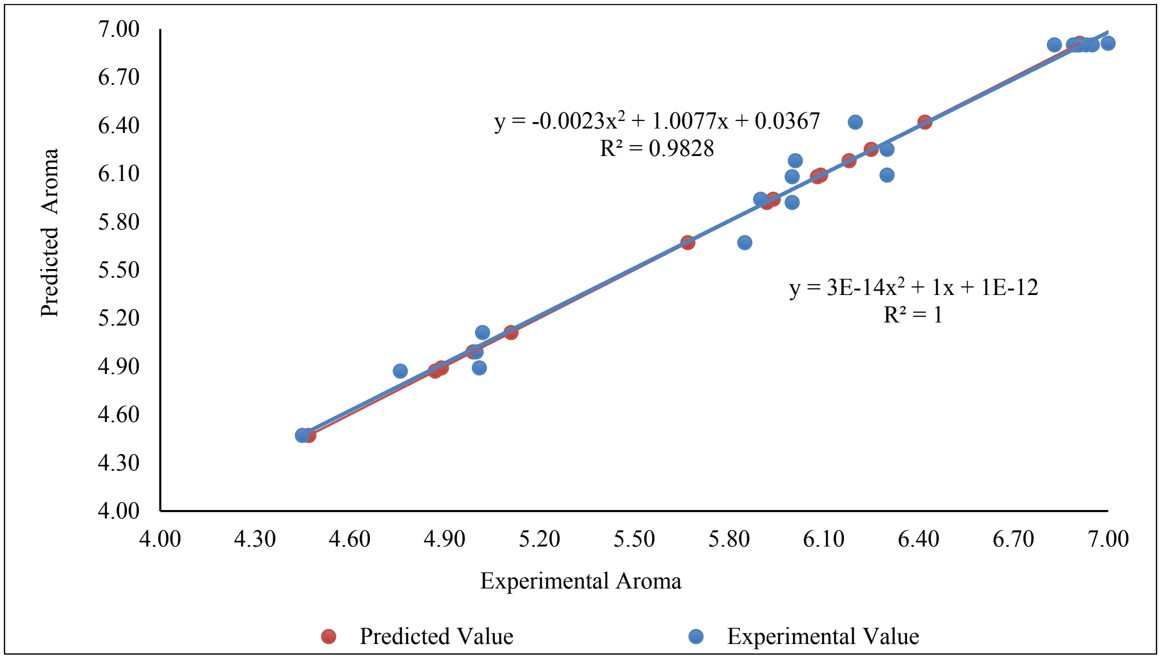

Fig. 4 Comparison of the predicted and experimental values for Aroma

A comparison of the experimental and predicted values for aroma is presented in Fig. 4. It was observed that the data points were approximately aligned in a straight line. The correlation between the predicted and experimental values yielded a coefficient of determination R^2 value of 0.982. This high coefficient of determination indicates a strong agreement between the predicted and experimental (measured) values for aroma. The 'Fit and Diagnostic Case' statistics showed that the deviation between the predicted and experimental values (residuals) for aroma is in the range of -0.003 to 0.207. Therefore, the generated quadratic model demonstrates accuracy in predicting the aroma of aerial yam-soybean flour blends.

IV. CONCLUSION

According to the numerical optimization results, extrudates with the best sensory property scores of 5.34 for texture, 4.91 for taste, 6.97 for appearance, and 5.80 for aroma would be produced at a barrel temperature of 114.12 °C, a screw speed of 100.56 rpm, and a feed moisture content of 38.02%, with a desirability of 0.943. Comparing the predicted and experimental (measured) results for the optimum responses, it is evident that there is an excellent correlation between the predicted and experimental values for the responses (texture, taste, appearance, and aroma).The comparison of the predicted and experimental values for the sensory characteristics (texture, taste, appearance, and aroma) shows that the data points are approximately aligned in a straight line very close to each other. The correlation between the predicted values and the experimental values yields a high coefficient of determination R^2, indicating a strong correlation. The 'Fit and Diagnostic Case' statistics show a low range of deviations between the predicted and experimental values for the sensory characteristics. Therefore, the generated quadratic model demonstrates accuracy in predicting the sensory characteristics of the aerial yam-soybean flour blend and is thus validated.

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