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Numerical Modeling for Optimizing and Validating Extrusion Process Conditions for the Proximate Composition of Blended Aerial Yam and Soybean Flours

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Abstract

The need to formulate/develop acceptable food products from neglected food crops, and control the process conditions in order to produce extrudates with the desired quality, result in optimization. This study is therefore aimed at numerical modeling for the optimization and validation of extrusion process conditions for the proximate composition of blended aerial yam and soybean flours. Design Expert (version 11.0.1) was used in the experimental design, with a three-factor experimental set up at five levels each, with barrel temperature, screw speed and feed moisture levels, as the independent factors. The blended flour was extruded using a single-screw extruder. Results of the laboratory analysis of the extrudates showed proximate compositions of 4.03 to 5.90% ash, 3.10 to 7.02% moisture content, 2.70 to 4.6% fibre, 24.57 to 36.79% protein, and 11.39 to 35.35% crude fat (lipid). Numerical optimization of the extrusion process conditions indicated optimal barrel temperature, screw speed and feed moisture of 112.11°C, 136.49 rpm and 34.65%, respectively, and optimum ash, moisture, fibre, protein, and lipid contents of 5.46%, 4.73%, 4.04%, 36.79%, and 22.59%, respectively, with a desirability of 0.857. The experimental values obtained were 5.39% for ash, 4.77% for moisture content, 4.11% for fibre, 36.72% for protein, and 22.64% for lipid. Comparison of the predicted and experimental results for the optimum predicted and measured responses showed excellent correlation between the predicted and experimental values for the responses. Therefore, the generated quadratic model has the accuracy to predict the proximate compositions of the extruded aerial yam and soybean flour blend, and is validated.

Keywords: Numerical Modeling, Optimization and Validation, Extrusion Process Conditions, Single-Screw Extruder, Aerial Yam-Soybean Flour.

Introduction

Optimization process is essential in the area of formulation/development of acceptable food products from neglected food crops, and in controlling the process conditions or parameters in order to produce extrudates with the desired quality (Umoh *et al.*, 2021; Umoh *et al.*, 2024a).

Aerial yam (*Dioscorea bulbifera*), is a perennial, semi-wild food crop that grows on vines, climbing unto poles and trees, which belongs to the yam family, *Dioscoreaceae*. The bulb is eaten after cooking, on peeling off the hard back. Its common names are: air yam, air potato, bitter yam, aerial yam, potato yam, among others (Umoh *et al*., 2021). Aerial yam is recorded to be an unpopular yam among the edible yam species which, unlike the traditional yam, produces aerial bulbils that look like potatoes, hence, the name aerial/air potatoes (Ojinnaka *et al*., 2017).

According to Princewill-Ogbonna and Ezembaukwu (2015), processing aerial yam to flour, can help to reduce the over dependent on wheat flour for our baked products and post-harvest losses. Aerial yam flour can be used as composite flour in the production of cookies. It has an array of good starch contents, functional and rheological properties which indicate a wider potential for utility of aerial yam flour in the food industry as thickeners, drug/tablet binders in the pharmaceutical industries.

Soybean (*Glycine max*), a major oil seed 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%. Soybean is mainly cultivated for its seeds, used commercially as human food and livestock feed, and for the extraction of oil. Soy foods have a high protein content and high protein utilization, leading to the highest amount of protein gained (Umoh *et al*., 2024b). In the last three decades, soy protein has been used in foods in increasing amounts to supply low-cost, high-quality protein with important functional properties. Soybean has been recognized as so versatile, that it can be processed into a wide variety of food products (Iwe, 2003). Soybeans can be processed to produce a texture and appearance similar to many other foods. For example, soybeans are the primary ingredient in many dairy product substitutes (e.g., soy milk, margarine, soy ice cream, soy yogurt, soy cheese, and soy cream cheese) and meat alternatives (e.g., veggie burgers).

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. 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 (Umoh and Iwe, 2023; Umoh *et* al., 2024a; Umoh *et al*., 2024b). Extrusion cooking is preferred over other food processing techniques because it is a continuous, highly productive process that results in significant nutrient retention because of the high temperature and short time required. Extrusion also offers excellent opportunity to modify hydration properties and to improve paste stability and functionality of food matrices, by tailoring the processing conditions (Terefe *et al*., 2022).

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 (Aydar, 2018; Umoh *et al*., 2024b). According to Nkesiga *et* al. (2021), Response Surface Methodology (RSM) is an important statistical method for experimental design, model construction, analysis of factors and optimal search for conditions. Response surface methodology has the benefit of concurrently varying independent variables to have a useful model of overall variations in response.

Response surface methodology (RSM) is frequently used in the production of extruded food products and aids in optimizing various process operational variables. 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 (Yagci and Gogus, 2009; Seth and Rajamanickam, 2012).

Research Problem

One of the major concerns of food processors, adopting food extrusion processing, has been the production of nutritious ready-to-eat/expanded food products. The need to select appropriate extrusion process conditions or parameters, through optimization, that would produce expanded food products with optimum quality characteristics is quite imperative, hence, the need for modeling and optimization of the process variables.

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 (Umoh *et al*., 2024b).

Aim/Objectives of the Study

This study aims at modeling, optimizing and validating the extrusion process parameters (barrel temperature, screw speed, and feed moisture) for the proximate composition of extrudates made from blended soybean and aerial yam flours. The specific objectives are to:

- Select appropriate model/equations for the optimization of the extrusion conditions (barrel temperature, screw speed, and feed moisture) for proximate

composition (ash, moisture, fibre, protein, and lipid) of blended aerial yam and soybean flours.
- Optimize and validate the extrusion process conditions for the responses (proximate compositions), using response surface methodology (RSM).

Materials and Methods

Preparation of Aerial Yam Flour

Aerial yam flour was prepared according to the method described by Umoh and Iwe (2022). The Aerial yam bulbs were cleaned and sorted to remove unwanted materials, before peeling with knife, washed with cleaned water and sliced to 10 mm thickness using knife. The slices (chips) were then dried, using an oven at a temperature of 60 °C for 12 h. The dried slices (chips) were then milled using a disc attrition mill and sieved using laboratory sieve of 600μm aperture size. The flour obtained was packaged in a polyethene bag for subsequent use.

Preparation of Soybean Flour

Soybean flour was prepared according to the method described by Umoh and Iwe (2022). Seeds were screened to remove foreign materials, splits, and damaged beans. This was followed by washing and roll boiling at 100 °C for 30 minutes. It was then oven -dried at a temperature of 70 °C for 12 h, and milled in a disc attrition mill. The milled full-fat soybean was sieved using a 100-mesh standard sieve. The flour obtained was then stored in air- tight polyethene bag at room temperature for further use.

Preparation of Sample Blend

The Aerial yam–Soybean flour blend was prepared in the ratio of 25:75, expressed in percentage as 25% aerial yam flour and 75% soybean flour.

Experimental Design/Statistical Analysis

Design Expert (version 11.0.1), a Statistical Computer Application Software Package was used in the experimental design. Central Composite Randomized Design (CCRD) was used with a three-factor experimental set up at five levels each, with barrel temperature (X_1), screw speed (X_2) and feed moisture levels (X_3) as the independent factors (Table 1). Coded values for the independent variables used were -2, -1, 0, 1, 2, where -2 represents the lowest, 0 represents the medium (mid-point), and 2 represents highest levels, respectively (Tables 1).

Table 1: Coded and Actual values of different Experimental variables

Factors	Units	Codes	Levels					Interval of Variation
			-2	-1	0	1	2	
Barrel temp.	°C	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

The empirical expression for the responses is represented as:

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

Where Y = Response, β_o = 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.

Extrusion Processing

This was done according to the method described by Umoh and Iwe (2022), using a single-screw laboratory scale extruder. Two hundred grams (200 g) of the flour blend was precisely estimated and preconditioned by the ideal moisture levels, permitted to remain for around two minutes (2 min) to guarantee uniform hydration of the natural substance. The extruder was turned on, and the barrel temperatures and the screw speeds of the extruder were set accordingly. The natural substance was taken care of, through the container, into the extruder. The extrudates were gathered as they exit through the die, dried, and packaged in impenetrable zip lock polyethylene sacks for additional research facility investigation.

Determination of Proximate Composition

The following Proximate analyses of the extruded aerial yam-soybean flour blend were carried out according to the methods described by Umoh and Iwe (2022):

Moisture Content

The weight of a washed and oven dried beaker was taken after cooling in a desiccators (a). Two grams (2 g) of the flour blend sample was introduced into the weighed beaker and the weight of the beaker plus sample was taken (b). The beaker with its content was dried in an oven at 105°C for 4h after which was quickly transferred into a desiccator to cool, then reweighed. This procedure was repeated till a constant weight was obtained (c).

Calculation:

$$Moisture\ (\%) = \frac{\text{Loss in weight (b−c)}}{\text{weight of sample (b−a)}} \times 100$$

Ash Content

A crucible with lid was ignited in a muffle furnace, Model SXL-1200, at 105 °C for 1 hr. It was then transferred to a dessicator to cool and weighed (a). Two grams (2 g) of the flour blend sample was put into the pre-weighed crucible and its content (flour sample) was taken (b). The crucible and its content was charred using Bunsen flame in a fume cupboard, until smoking ceased. It was then moved to muffle furnace, at 550 °C for 2 h. The crucible taken out, cooled, covered and placed in a dessicator and weighed (c).

Calculation:

$$Ash\ (\%) = \frac{\text{Weight of Ash (b−c)}}{\text{Weight of Sample (b−a)}} \times 100$$

Crude Fibre

Two grams (2 g) of the sample was defatted with petroleum ether for 2 h. It was boiled for 30 minutes with 200 ml of Sulphuric acid (H_2SO_4) solution, filtered through linen on a fluted funnel and washed with boiling water until the washings were no longer acidic. The residue was moved to a beaker and boiled for an additional 30 minutes with 200 ml of Sodium hydroxide (NaOH) arrangement, separated and the last residue washed with bubbling water a few times until was base (NaOH) free. The residue was at long last washed two times with methanol, quantitatively moved into a pre-gauged cauldron, and broiler dried at 105 °C (Io). It was burned in a heater at 550 °C, cooled in a dessicator and gauged (Ia). The misfortune in weight after cremation was likewise taken.

Calculation:

$$Crude\ \text{fibre}\ (\%) = \frac{\text{Ia−Io}}{\text{Weight of original Sample taken}} \times 100$$

Crude Protein

Crude protein was determined by Kjeldahl method. One gram (1 g) of the flour sample was accurately weighed into a standard 250 ml Kjeldahl flask containing 1.5 g Copper sulphate ($CuSO_4$) and 1.5 g Sodium sulphate (Na_2SO_4) as catalyst and 5 ml concentrated Sulphuric acid (H_2SO_4). The kjeldahl flask (digestion) was placed on a heating mantle and was heated gently to prevent frothing, for some hours until a clear bluish solution was obtained. The digested solution was allowed to cool and was quantitatively transferred to 100ml standard flask, made up to the mark with distilled water. Twenty millilitres (20 ml) portion of the digest was pipette into a semi micro kjeldahl distillation apparatus and treated with equal volume of 40% Sodium hydroxide (NaOH) solution. The ammonia evolved was steam distilled into 100 ml conical flask containing 10ml solution of saturated boric acid to which 2 drops of Tashirus indicator (double indicator) had been added. The tip of the condenser was immersed into the boric acid – double indicator solution and then the distillation continued until about 2/3 of the original volume was obtained. The tip of the condenser was then rinsed with a few millilitres of distilled water in the distillate which was then titrated with 0.1M Hydrochloric acid (HCl) solution until a purple-pink end-point was observed. A blank determination was also carried out in the similar manner as described above except for the omission of the sample. The crude protein was obtained by multiplying the % Nitrogen content by a factor (6.25). Crude protein = % Nitrogen X factor.

Calculation:

$$\frac{(\text{Sample titre}-\text{blank titre})0.1\times 0.014}{\text{Weight of Sample}} \times \frac{100}{20} \times \frac{100}{1} \times 6.25$$

Crude Fat (Lipid)

Two grams (2 g) of the flour blend sample was weighed into extraction thimble, which had already been washed, oven dried and lightly plugged with cotton wool. One hundred and fifty millilitres (150 ml) of petroleum ether with boiling point between 35 to 60 ℃, was poured into a 500 ml capacity round bottom flask. The soxhlet extractor was fitted into the round bottom flask which was seated on a heating mantle. The soxhlet apparatus was assembled and allowed to reflux for about 4 h. The extract was poured into a dried pre-weighed beaker (W_1) and the thimble rinsed with a little quantity of the ether back to the beaker. The beaker was heated on a steam bath to drive off the excess solvent, cooled in a desiccator and weighed (W_2).

Calculation:

$$\text{Crude fat (\%)} = \frac{\text{Weight gain in flask (W2}-\text{W1)}}{\text{Weight of Sample}} \times \frac{100}{1}$$

Model Selection for Optimization and Validation of Extrusion Process Conditions

Design Expert (version 11.0.1), a statistical software package for experimental design was used to analyze and generate the model equations for the responses (ash, moisture content, fibre, protein and lipid). In selecting suitable model for the extrusion process conditions of the responses, the highest order polynomial, where the additional terms are significant and the model is not aliased, insignificant lack-of-fit and the maximization of the Adjusted and predicted correlation coefficient (Adjusted R^2 and Predicted R^2) were considered. Considerations were also given to higher coefficient of determination (R^2) and lower standard deviation values (Aydar, 2018).

The optimization of the extrusion process conditions (barrel temperature, screw speed and feed moisture) was carried out using numerical method in Response Surface Methodology (RSM), with the optimization goals of maximizing the barrel temperature and screw speed, and then possible range for the feed moisture. In order to optimize the extrusion process conditions by numerical method, which finds a point that maximizes the desirability function, equal importance of 3 was assigned to all the three extrusion process conditions and the responses.

The main criteria and the desired goals for each process condition and the response are presented in Tables 2.

Table 2: Criteria for Numerical Optimization of Extrusion process Conditions for Proximate Composition

Extrusion criteria	Unit	Lower limit	Upper limit	Optimization Goal	Relative Importance
Barrel Temp	°C	95.00	115.00	Maximize	3
Screw Speed	*rpm*	85.00	145.00	Maximize	3
Feed Moisture	%	31.00	39.00	Range	3
Ash	%	4.03	5.90	Range	3
Moisture Content	%	3.08	7.02	Range	3
Fibre	%	2.70	4.67	Range	3
Protein	%	24.57	36.79	Range	3
Lipid	%	11.39	35.35	Range	3

Results and Discussions

The results of the proximate composition of the extruded aerial yam and soybean flour blends are presented in Table 3.

Table 3: Proximate composition of Extruded Aerial yam and Soybean flour blend

S/N	BT (°C)	SS (rpm)	FM (%)	Ash (%)	Moisture content (%)	Fibre (%)	Protein (%)	Crude fat (lipid) (%)
1	105	115	31	5.07±0.003	3.19±0.004	3.57±0.002	35.89±0.071	23.86±0.005
2	105	115	35	4.61±0.003	3.86±0.004	3.26±0.001	25.88±0.199	11.49±0.004
3	105	115	35	4.56±0.003	3.85±0.003	3.19±0.001	25.86±0.199	11.41±0.004
4	105	85	35	4.80±0.002	4.20±0.003	3.41±0.001	31.89±0.177	35.35±0.011
5	100	130	33	5.48±0.002	3.10±0.001	3.79±0.002	32.88±0.049	24.96±0.014
6	110	100	37	5.39±0.001	3.78±0.001	3.97±0.002	32.08±0.127	25.83±0.016
7	100	100	37	4.20±0.003	7.02±0.003	2.70±0.001	24.57±0.078	16.79±0.062
8	110	130	33	5.21±0.004	4.86±0.003	3.90±0.002	35.14±0.021	19.11±0.006
9	105	115	35	4.67±0.003	3.87±0.004	3.21±0.001	25.84±0.199	11.43±0.004
10	115	115	35	5.90±0.002	3.21±0.002	4.67±0.003	35.97±0.099	25.85±0.007
11	95	115	35	5.19±0.001	3.47±0.002	3.58±0.002	32.05±0.120	30.54±0.011
12	105	115	39	4.03±0.002	4.77±0.003	2.96±0.003	30.17±0.099	19.46±0.024
13	105	115	35	4.69±0.003	3.82±0.003	3.20±0.001	25.880.199	11.39±0.004
14	100	100	33	4.37±0.004	3.47±0.003	2.98±0.001	33.25±0.148	24.90±0.007
15	110	130	37	5.01±0.002	3.08±0.002	3.70±0.002	32.98±0.249	20.34±0.012
16	110	100	33	4.96±0.001	3.17±0.002	3.89±0.002	34.59±0.092	25.71±0.008
17	105	145	35	5.32±0.002	3.55±0.001	4.05±0.003	36.79±0.004	28.90±0.121
18	100	130	37	4.39±0.002	3.69±0.004	3.85±0.001	30.26±0.021	23.62±0.004
19	105	115	35	4.65±0.003	3.89±0.004	3.24±0.001	25.87±0.199	11.46±0.004
20	105	115	35	4.57±0.003	3.85±0.004	3.22±0.001	25.83±0.199	11.51±0.004

Note: Values are mean ± standard deviation of triplicate determination.

BT = Barrel Temperature, SS = Screw Speed, FM = Feed Moisture.

Ash

The results of the ash contents of the extruded aerial yam flour blends ranged from 4.03 to 5.90% (Table 3). This range of values is higher than 1.45 to 2.56 for sorghum-based extruded product supplemented with defatted soy meal flour (Tadesse *et al*., 2019); 1.88 to 2.91% for root and tuber composite flour noodles (Akonor *et al*., 2017); 1.33 to 2.69% for selected Aerial yam cultivar and African Breadfruit extruded snacks (Olatoye and Arueya, 2021); and 1.67 to 3.00% for high quality cassava-Tiger nut extruded snacks (Kareem *et al*., 2015). This is an indication that extruded aerial yam-soybean flour blend is a potentially rich source of mineral elements.

Moisture Content

The results of the moisture contents of the extruded aerial yam and soybean flour are presented in Table 3. The moisture contents of the extrudates varied between 3.10 and 7.02%. The observed low range of values for moisture content indicates that the extrudates can store for a long time without spoilage due to microbial activities. This range of values is low compared to 8.15 to 8.66% for sorghum-based extruded product supplemented with defatted soy meal flour (Tadesse *et al*., 2019); 5.97 to 6.59% for selected Aerial yam cultivar and African Breadfruit extruded snacks (Olatoye and Arueya, 2021); and 5.25 to 8.05% for high quality cassava-Tiger nut extruded snacks (Kareem *et al*., 2015). In dry food systems, moisture content of between 6 and 10% has been established to prolong the shelf life of foods, beyond which the storability of the system could be impeded by chemical and microbiological agents (Brncic *et al*., 2006).

Fibre

The results of the fibre contents of the extruded aerial yam and soybean flour blends are presented in Table 3. The fibre content varied between 2.70 and 4.67%. This range of values is high compared to 0.83 and 1.58% for sorghum-based extruded product supplemented with defatted soy meal flour (Tadesse *et al*., 2019); 0.78 to 0.99% for selected Aerial yam cultivar and African Breadfruit extruded snacks (Olatoye and Arueya, 2021); and 3.81 to 4.26 for high quality cassava-Tiger nut extruded snacks (Kareem *et al*., 2015). The high range of values for fibre content is an indication that extrudates produced from aerial yam and soybean flour blends is a potential rich source of dietary fibre, which is necessary in the movement of food bowel and helps in the prevention of obesity, diabetes, cancer of the colon and other diseases of the gastro-intestinal tract of man.

Protein

The results of the protein contents of the extruded aerial yam and soybean flour blends are presented in Table 3. The results ranged from 24.57 to 36.79%. The observed range of values is higher, compared to 12.20 to 20.85% for sorghum-based extruded product supplemented with defatted soy meal flour (Tadesse *et al*., 2019); 10.90 to 14.26% for root and tuber composite flour noodles (Akonor *et al*., 2017); 8.80 to 13.59% for selected Aerial yam cultivar and African Breadfruit extruded snacks (Olatoye and Arueya, 2021); and 3.09 to 5.64% for high quality cassava-Tiger nut extruded snacks (Kareem *et al*., 2015). The high range of values for protein in the extrudates is attributed to the higher proportion of soybean flour (75%), compared to the proportion of aerial yam flour (25%) in the flour blend; Soybean has been reported to contain appreciable high percentage of protein. It can therefore be inferred that extrudates produced from aerial yam-soybean flour blends, at the ratio of 1:3 (25%:75%), is a potential rich source of protein required by humans for proper growth and development.

Crude Fat (Lipid)

The results of the percentage composition of lipid in the extruded aerial yam and soybean flour blend are presented in Table 3. The results of the lipids contents ranged between 11.39 and 35.35%. This observed range of values is higher compared to 3.06 to 3.96% for sorghum-based extruded product supplemented with defatted soy meal flour (Tadesse *et al*., 2019); 6.40 to 9.07% for selected Aerial yam cultivar and African Breadfruit extruded snacks (Olatoye and Arueya, 2021); and 0.42 to 22.28% for high quality cassava-tiger nut extruded snacks (Kareem *et al*., 2015). The high crude fat content in the extrudates may be attributed to the full-fat soybean flour used as a component of the blends. The high fat content of the full-fat soybean flour may be attributed to the high crude fat contents of the extruded aerial yam and soybean flour blends.

Table 4: Coefficient of Regression/ANOVA for proximate composition

	Ash (%)		Moisture content (%)		Fibre (%)		Protein (%)		Lipid (%)	
	Coeff.	p-value	Coeff.	p-value	Coeff.	p-value	Coeff.	p-value	Coeff.	p-value
X_0	113.01		-236.34		70.38		1937.40		3176.87	
Linear										
X_1	-2.21	< 0.0001	1.39	0.0297	-14.47	< 0.0001	-19.12	0.0001	-35.83	0.1204
X_2	0.3807	0.0010	-0.0573	0.0051	0.2606	< 0.0001	-2.37	0.0011	-3.12	0.0053
X_3	-0.8726	< 0.0001	9.72	0.0002	-0.4255	0.0042	-44.25	< 0.0001	-62.04	0.0078
Interaction										
X_1X_2	-0.0024	0.0019	0.0078	< 0.0001	-0.0037	< 0.0001	-0.0065	0.1637	-0.0316	0.0004
X_1X_3	0.0186	0.0015	-0.0664	< 0.0001	0.0013	0.7448	0.0829	0.0277	0.1350	0.0135
X_2X_3	-0.0065	0.0011	-0.0223	< 0.0001	0.00025	0.8449	0.0267	0.0320	0.328	0.0538
Quadratic										
X_1^2	0.00895	< 0.0001			0.0091	< 0.0001	0.0821	< 0.0001	0.164	<0.0001
X_2^2	0.00046	0.0017			0.00057	0.0001	0.0095	< 0.0001	0.0227	<0.0001
X_3^2	-0.00063	0.3255			0.0031	0.5697	0.4517	< 0.0001	0.6223	<0.0001
Test for model adequacy										
R^2	0.9650		0.9225		0.9730		0.9746		0.9844	
Pred. R^2	0.7366		0.7301		0.7969		0.8061		0.8762	
Model F-value	30.65		25.79		40.09		42.71		70.22	
Lack of fit	9.24		263.25		31.84		3765.61		1493.29	

Note: X_0 = intercept, X_1 = Barrel temperature, X_2 = Screw speed, X_3 = Feed moisture. Significance at $p < 0.005$.

The results of Regression analysis/ANOVA of the models for optimization/validation of extrusion process conditions for the responses (proximate compositions of aerial yam and soybean flour blend) are presented in Table 4.

Model Selection/Equation for Optimization/Validation of Extrusion Process Conditions

Model Selection/Equation for Ash

Quadratic model was selected to predict the percentage ash composition in the extrusion process.

Consequently, the final regression model for ash is given in Equation 3.1 as:

$$\mathbf{AS = 113.01 - 2.21BT + 0.3807SS - 0.8726FM - 0.0024BTSS + 0.0186BTFM - 0.0065SSFM + 0.00895BT^2 + 0.00046SS^2 - 0.0063FM^2} \quad [3.1]$$

Where:

AS = Ash content (%), BT= Barrel Temperature (°C), SS = screw speed (rpm), FM= Feed Moisture

In Equation 3.1, the positive terms signify direct relationship between the extrusion process conditions and their interactions with the ash content, while the negative terms signify an inverse relation between them. Only screw speed had direct relationship with the ash content, while barrel temperature and feed moisture showed inverse relationship with the ash content.

Analysis of variance (ANOVA) showed the model F-value of 30.65 and *p*-value of < 0.0001 signifying that the model is significant (Table 4). The "Lack of fit" F-value of 9.24 implies that the "Lack of Fit" is not significant relative to the pure error. This model can be used to navigate the design space.

The model was significant with a low probability value of < 0.0001 and a satisfactory coefficient of determination, R^2 of 0.9650 (Table 4). The high coefficient of determination is an indication of an excellent correlation between the independent variables (barrel temperature, screw speed and feed moisture). It is also an indication that the response model for ash content is adequate, and can explain 96% of the total variability in the response.

Model Selection/Equation for Moisture Content

Two factorial interaction (2FI) model was selected to predict the percentage moisture content in the extrusion process.

Consequently, the final regression model for moisture content is given in Equation 3.2 as:

$$\mathbf{MC = -236.34 + 1.39BT - 0.0573SS + 9.72FM + 0.0078BTSS - 0.0664BTFM - 0.0223SSFM} \quad [3.2]$$

Where: MC = Moisture content (%), BT = Barrel Temperature (°C),SS = screw speed (rpm), FM = Feed Moisture.

In Equation 3.2, the positive terms signify direct relationship between the extrusion process parameters and their interaction with percentage moisture content, while the negative terms signify an inverse relation between them. Barrel temperature and feed moisture showed direct relationship with moisture content, while screw speed had inverse relationship with moisture content.

The model F-value of 25.79 and *p*-value of < 0.0001 signify that the model is significant. The "Lack of fit" F-value of 263.26 implies that the "Lack of Fit" is not significant relative to the pure error. This model can be used to navigate the design space.

The model was significant with a low probability value of < 0.0001 and a satisfactory coefficient of determination, R^2 of 0.9225 (Table 4). The high coefficient of determination is an indication that an excellent correlation existed between the independent variables (barrel temperature, screw speed and feed moisture). It is also an indication that the response (moisture content) model can explain 95% of the total variability in the response.

Model Selection/Equation for Fibre

Quadratic model was selected to predict the percentage fibre composition in the extrusion of aerial yam and soybean flour blend.

Consequently, the final regression model for fibre is given in Equation 3.3 as:

$$\mathbf{FB = 70.38 - 1.47BT + 0.26067SS - 0.4255FM - 0.0037BTSS + 0.0013BTFM + 0.00025SSFM + 0.0091\ BT^2 + 0.00057SS^2 + 0.0031\ FM^2} \quad [3.3]$$

Where:

FB = Fibre (%), BT= barrel temperature (°C), SS = screw speed (rpm), FM = Feed Moisture

In Equation 3.3, the positive terms signify direct relationship between the extrusion process parameters and their interaction with percentage fibre content, while the negative terms signify an inverse relation between them. Barrel temperature and feed moisture, had inverse relationship with fibre content, while screw speed showed a direct relationship with fibre content.

From the results of Regression analysis/ANOVA, the model F-value of 40.09 and *p*-value of < 0.0001 signify that the model is significant.

The "Lack of Fit F-value" of 31.84 (Table 4), implies that the "Lack of Fit" is not significant relative to the pure error. This model can be used to navigate the design space.

The model was significant with a low probability value of < 0.0001 and a satisfactory coefficient of determination, R^2 of 0.9730 (Table 4). The high coefficient of determination suggests that an excellent correlation existed between the independent variables (barrel temperature, screw speed and feed moisture), indicating that the response (fibre content) model can explain 97% of the total variability in the response.

Model Selection/Equation for Protein

In order to predict the percentage protein composition in the extrusion process, the quadratic model was selected.

Consequently, the final regression model for protein is given in Equation 3.4 as:

$$\mathbf{PT = 1937.40 - 19.12\ BT - 2.37SS - 44.25FM - 0.0065BTSS + 0.0829BTFM + 0.0267SSFM + 0.0821BT^2 + 0.0095SS^2 + 0.4517FM^2} \quad [3.4]$$

Where:PT = Protein (%), BT= Barrel Temperature (°C), SS = Screw Speed (rpm),FM = Feed Moisture

In Equation 3.4, the positive terms signify direct relationship between the extrusion process conditions and their interaction with protein content, while the negative terms signify an inverse relation between them. All the extrusion process conditions (barrel temperature, screw speed and feed moisture showed inverse relationship with protein content, while screw speed had a direct relationship with protein content.

In Table 4, the model F-value of 42.71 and p-value of < 0.0001 signify that the model is significant. The "Lack of fit F-value" of 3765.61 implies that the "Lack of Fit" is not significant. This model can be used to navigate the design space.
The model was significant with a low probability value of < 0.0001 and a satisfactory coefficient of determination, R^2 of 0.9746 (Table 4). The high coefficient of determination is an indication that an excellent correlation existed between the independent variables (barrel temperature, screw speed and feed moisture). It is also an indication that the model can explain 97% of the total variability in the response.

Model Selection/Equation for Lipid

Quadratic model was selected to predict the percentage lipid composition in the extrusion process.
Consequently, the final regression model for crude fat is given in Equation 3.5 as:

$$\mathbf{LP = 3176.87 - 35.83BT - 3.12SS - 62.04FM - 0.0316BTSS + 0.1350BTFM + 0.0328SSFM + 0.1649BT^2 + 0.0227SS^2 + 0.6223FM^2} \quad [3.5]$$

Where: LP = Crude fat (%), BT= Barrel Temperature (°C), SS = Screw Speed (rpm), FM =Feed Moisture
In Equation 3.5, the positive terms signify direct relationship between the extrusion process parameters and their interaction with percentage lipid content, while the negative terms signify an inverse relation between them. The three extrusion process conditions (barrel temperature, screw speed and feed moisture) had inverse relationship with the lipid content.
The model F-value of 70.22 and p-value of < 0.0001 signify that the model is significant. The "Lack of fit" F-value of 1493.29 implies that the "Lack of Fit" is not significant. This model can be used to navigate the design space.
The model was significant with a low probability value of < 0.0001 and a satisfactory coefficient of determination, R^2 of 0.9844 (Table 4). The high coefficient of determination is an indication that an excellent correlation existed between the independent variables (barrel temperature, screw speed and feed moisture). It is also an indication that the model can explain 98% of the total variability in the response.

Optimization and Validation of the Extrusion Process Conditions

The optimization of the extrusion process conditions (barrel temperature, screw speed and feed moisture) was done using numerical method in response surface methodology (RSM), with the optimization goals of maximizing the barrel temperature and screw speed, and then possible range for the feed moisture (Table 5).

Table 5: Output for Numerical Optimization of Extrusion Process Parameters for Proximate composition

Extrusion criteria	Unit	Lower limit	Upper limit	Optimization Goal	Relative Importance	Output
Barrel Temp	°C	95.00	115.00	Maximize	3	112.11
Screw Speed	Rpm	85.00	145.00	Maximize	3	136.49
Feed Moisture	%	31.00	39.00	Range	3	34.65
Ash	%	4.03	5.90	Range	3	5.46
Moisture Content	%	3.08	7.02	Range	3	4.73
Fibre	%	2.70	4.67	Range	3	4.04
Protein	%	24.57	36.79	Range	3	36.79
Lipid	%	11.39	35.35	Range	3	22.59
Desirability						0.857

Results of the optimization process showed optimal barrel temperature, screw speed and feed moisture of 112.11 °C, 136.49 rpm and 34.65%, respectively, and optimum percentage ash, moisture, fibre, protein, and lipid contents of 5.46%, 4.73%, 4.04%, 36.79%, 22.59%, respectively, with a desirability of 0.857 (Table 5).

The predicted value for feed moisture was in the range of 31 to 39% at optimal value of 34.65%

For the responses, the optimization results for the goal of optimizing the range were 4.03 to 5.90% for ash, 3.08 to 7.02% for moisture content, 2.70 to 4.67% for fibre, 24.57 to 36.79% for protein, and11.39 to 35.35% for lipid.

A test run under the obtained optimal extrusion process parameters of barrel temperature (112.11°C), screw speed (136.49 rpm) and feed moisture (34.65%) was carried out in order to validate the quadratic model for the responses (proximate composition: ash, moisture content, fibre, protein, and lipid). The experimental values obtained were 5.39% for ash, 4.77% for moisture content, 4.11% for fibre, 36.72% for protein, and 22.64% for lipid (Table 5).

Table 6: Optimum Extrusion Process Parameters with Optimum Predicted Responses for Validation of Proximate Composition

Extrusion process parameter			Optimum Predicted Responses					Measured Responses					Desirability
BT (°C)	SS (rpm)	FM (%)	AS (%)	MC (%)	FB (%)	PT (%)	LP (%)	AS (%)	MC (%)	FB (%)	PT (%)	LP (%)	
112.11	136.49	34.65	5.46	4.73	4.04	36.79	22.59	5.39	4.77	4.11	36.72	22.64	0.857

Note: BT = Barrel temperature, SS = Screw speed, FM = Feed moisture, AS = Ash, MC = Moisture content, FB = Fibre, PT = Protein, LP = Lipid.

The optimal extrusion process conditions with optimum predicted responses for the validation of the proximate composition of the extruded aerial yam and soybean flour blends is presented in Table 6.

Comparison of the predicted and experimental results for the optimum predicted and measured responses shows that there was excellent agreement (correlation) between the predicted and experimental (measured) values for the responses (ash, moisture content, fibre, protein, and lipid).

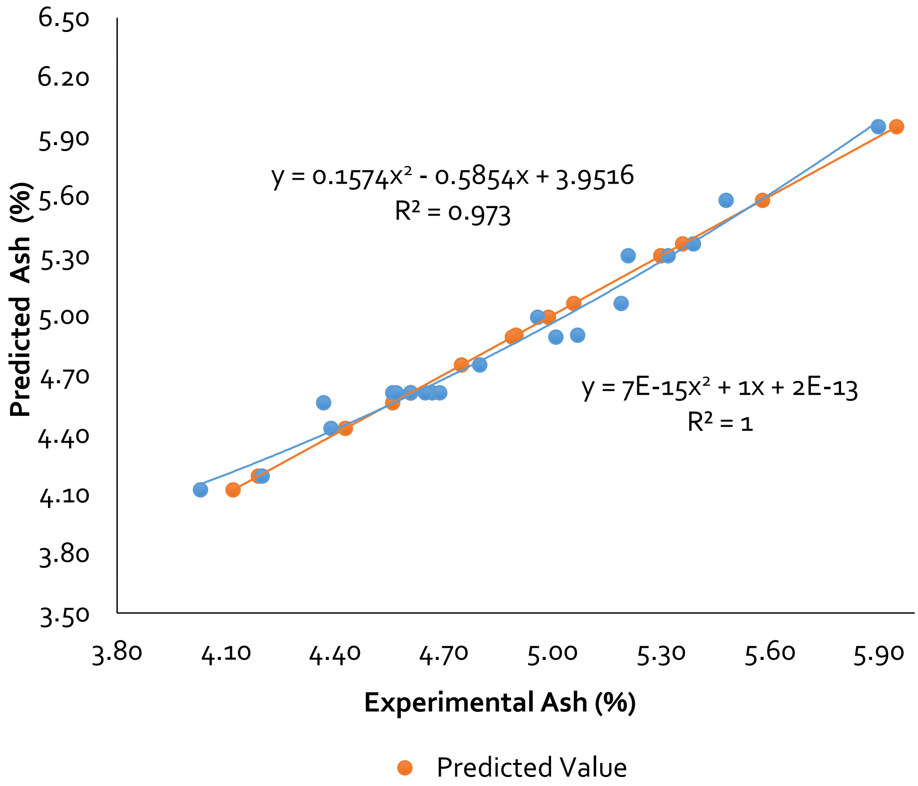

Fig. 1: Comparison of the predicted and experimental values for Ash

In Fig.1, the data were observed to spread approximately in a straight line. The correlation between the predicted and experimental values for the percentage ash composition gave an R^2 value of 0.973. This is an indication that the predicted values and experimental values had a perfect agreement. Therefore, the generated quadratic model has the accuracy to predict the percentage ash composition of the extruded aerial yam-soybeans flour blend, and is validated.

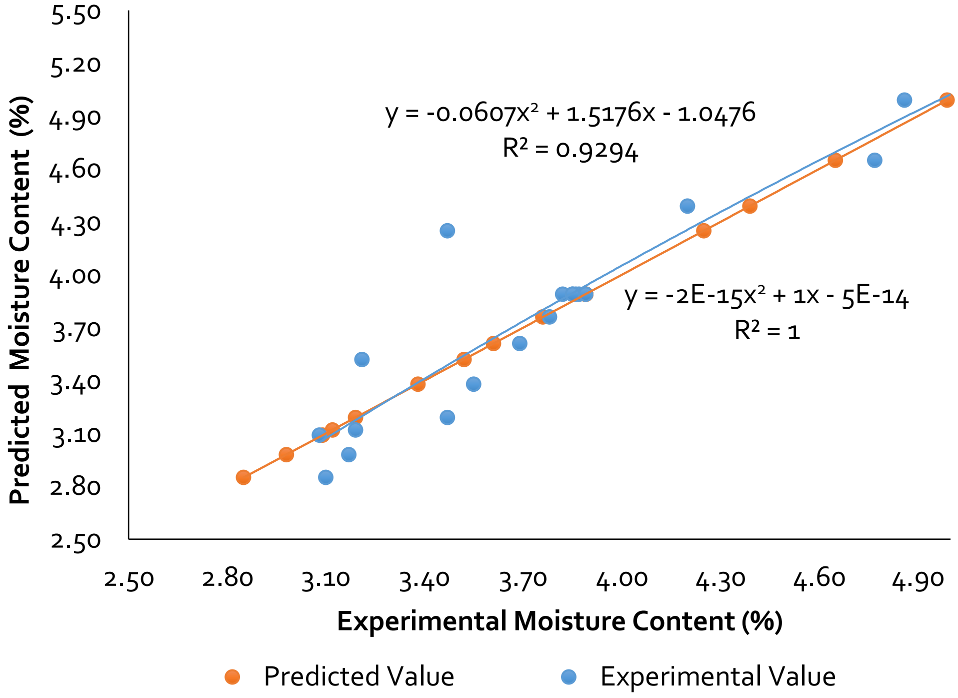

Fig. 2: Comparison of the predicted and experimental values for Moisture Content

Fig.2 shows comparison of the predicted and experimental values for moisture content of the extruded aerial yam and soybean flour blends.

From the plot, the data were seen to spread approximately in a straight line, and the correlation between the predicted and experimental values for the percentage moisture content gave an R^2 value of 0.929. This is an indication that the predicted values and experimental values had a perfect agreement. Therefore, the generated quadratic model has the accuracy to predict the percentage moisture composition of the extruded aerial yam-soybeans flour blend, and is validated.

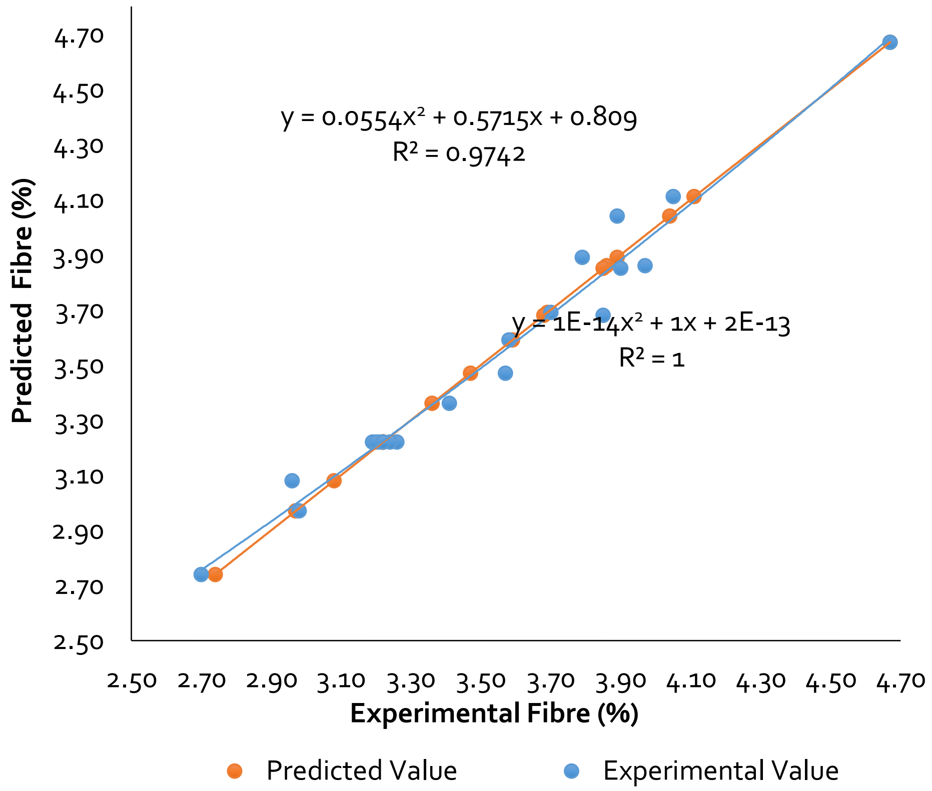

Fig. 3: Comparison of the predicted and experimental values for Fibre

The comparison of the predicted and experimental values for the percentage fibre composition of the extruded aerial yam-soybean flour blend is presented in Fig.3.

The points (data) were observed to spread approximately in a straight line, close to each other. The correlation between the predicted and experimental values gave an R^2 (coefficient of determination) value of 0.974, implying that the predicted values and experimental values had a perfect correlation. Therefore, the generated quadratic model has the accuracy to predict the fibre content of the extruded aerial yam-soybeans flour blend, and is validated.

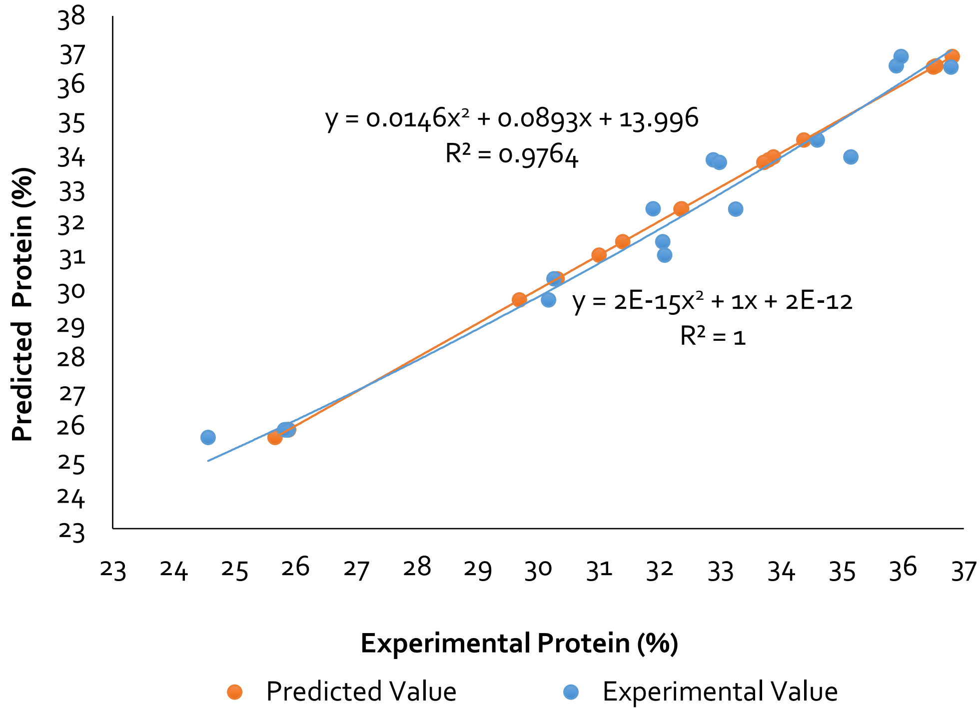

Fig. 4: Comparison of the predicted and experimental values for Protein

Fig.4 shows the comparison of the predicted and experimental values for the percentage composition of protein. Also, the data (the points) spread approximately in a straight line. The correlation between the predicted values and the experimental values gave a coefficient of determination, R^2 value of 0.976. The high value of coefficient of determination indicates a perfect correlation. The generated quadratic model has the accuracy to predict the percentage protein composition of the extruded aerial yam-soybeans flour blend, and is therefore validated.

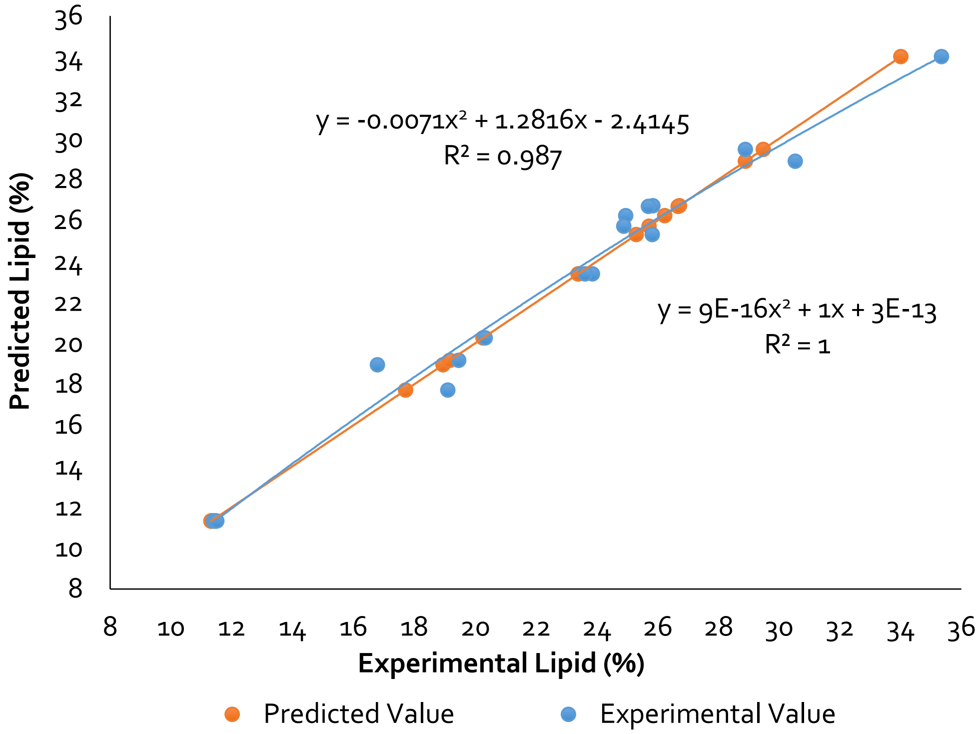

Fig. 5: Comparison of the predicted and experimental values for Lipid

The comparison of the predicted and experimental values for the percentage lipid composition of the extruded aerial yam and soybeans is presented in Fig.5. From the plot, the data were observed to spread approximately in a straight line, and close to each other. Also, the correlation between the predicted values and the experimental values produced a coefficient of determination, R^2 value of 0.987, implying that the predicted and experimental values had a certain degree of agreement. Therefore, the generated quadratic model has the accuracy to predict the percentage lipid composition of the extruded aerial yam-soybeans flour blend, and is validated.

Conclusions

This study has shown that quadratic model is best suited for the optimization and validation of extrusion process conditions (barrel temperature, screw speed and feed moisture) for the proximate compositions of blended aerial yam and soybean flours.

Optimization of the extrusion process conditions shows that optimal barrel temperature, screw speed and feed moisture of 112.11 °C, 136.49 rpm and 34.65%, respectively, would produce extruded products with optimum percentage ash, moisture, fibre, protein, and lipid contents of 5.46%, 4.73%, 4.04%, 36.79%, 22.59%, respectively, with a desirability of 0.857.

Comparison of the predicted and experimental results for the optimum predicted and measured responses show that there was excellent correlation between the predicted and experimental (measured) values for the responses (ash, moisture content, fibre, protein, and lipid).

Therefore, the generated quadratic model has the accuracy to predict the percentage ash, moisture, fibre, protein and lipid contents of the extruded aerial yam-soybeans flour blend (responses), and is validated.

Conflict of Interest

The authors declare that no conflicts of interest exist.

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