Process optimization for yam flour incorporated in expanded extrudates

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\textbf{ABSTRACT}

The effects of incorporation of water yam (\textit{Dioscorea alata} L.), feed moisture content, and extrusion conditions on physical characteristics of expanded extrudate were studied using response surface methodology. The mixture was prepared using maize grit, rice grit, and gram flour. Yam flour was incorporated at 10–20% level in the feed mix, and the moisture content of the feed was varied from 13% to 15%. The extrusion process was run at varied temperature conditions (90–110°C) in a single screw extruder. A numerical multi-response optimization technique was used for optimizing input variables. Lateral expansion (LE) and starch digestibility had significant (\(p < 0.05\)) positive effects due to yam incorporation, while density, water absorption index (WAI), and water solubility index (WSI) had a significantly negative effects. Feed moisture had a significant (\(p < 0.05\)) effects on product density and WSI positively. Barrel temperature had a significant (\(p < 0.05\)) positive effects on LE and starch digestibility where density and WAI had a significant negative effects. Optimum operating conditions for yam flour addition, feed moisture and barrel temperature were 20\%, 13.28\%, and 108.83°C, respectively. Corresponding to these process variable, predicted values were 144.65\% for LE, 0.222g/cm\textsuperscript{3} for density, 6.002 g/g for WAI, 7.217\% for WSI, and 305.15 \(\mu\)g/g for maltose content with desirability 0.848. The extrusion conditions and response variables reveal the possibility of using yam to produce extruded expanded snacks.

\textbf{INTRODUCTION}

Snacks are ready-to-eat convenient, easily manageable foods that can fulfill small hunger.\textsuperscript{[1,2]} One of the cost-efficient, versatile, and environmentally friendly technology for manufacturing snacks is the extrusion cooking process.\textsuperscript{[3]} In extrusion processing, the shear force causes friction between ingredients and the extruder surface, and ingredients themselves which results in compaction, size reduction, phase transition, and molecular breakdown of food materials in a short time. When the ingredients are exposed to high temperature and high shear force leaves the extruder, the mixed mass expands due to instantaneous vaporisation.\textsuperscript{[4]} The physical and sensory properties of an extruded product are generally affected by different extrusion parameters, such as screw speed, barrel temperature, and other feed variables.\textsuperscript{[4,5]} Extrusion results in degradation of starch releasing of reducing sugars\textsuperscript{[4]} such as maltose. The sweetness, imparted by sugars, is positively correlated with consumer

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Supplemental data for this article can be accessed on the publisher’s website.

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acceptability. Rice, maize, potato, and gram are used as ingredients for the preparation of expanded extruded snacks.

Extrusion of edible roots and tubers-based flour is gaining popularity in both research and commercial sectors because of their cheaper price and high starch content. Production of extruded snacks from such food source also helps diversifying ingredients resources. Water yam or yam (Dioscorea alata L.) belongs to the Dioscorea genus and are edible, highly starchy root tubers, which is one of the staple foods in the tropics has been attributed to the high digestibility. Its starch is present in the form of small granules. It is essential to establish the effects of extrusion variables on the characteristics of extruded yam products. Yet, a few scientific studies have been reported for using of yam in extrusion. A study on single screw extrusion of yam flour by Sebio and Chang showed a negative relationship of moisture content with lateral expansion and a positive relationship with water solubility index (WSI). Similarly, a study of Oke, Awonorin based extrusion of yam in a single screw extruder found an decrease in expansion ratio with an increase in screw speed. Extrusion of yam–corn–rice mix in a twin screw extruder demonstrated a proportional effect of barrel temperature on expansion ratio; however, no effect of extrusion variables was observed on WSI. Adams et al. used yam–baobab–tamarind flour blends in extrusion cooking with significantly improved physicochemical properties of extrudates, justifying promising future of yam in the snacks industry. In Nepal, yam has not been used for industrial purposes. It is essential to find the ways for using yam in food manufacturing to help food security and uplifting the livelihood of people associated with yam production. The general aim of this work was to explore the possibility of using yam in the manufacture of extruded expanded snacks.

MATERIALS AND METHODS

Raw materials preparation

Maize grit, rice grit, and gram flour were provided by CG Foods (Nepal) Pvt. Ltd., an extruded snack manufacturer located in Nawalparasi district, Nepal. Water yam was purchased from Pancha-Kanya, Sunsari district, Nepal. It was washed, trimmed, and peeled. After peeling the yam was immersed in 2% NaCl solution for 30 min to prevent browning reactions. It was sliced 3–5 mm thick and the slices were dipped in a mixture of 0.5% KMS (potassium metabisulphite) and 0.5% citric acid solution for half an hour to prevent further browning. Cabinet dryer was operated at 60 ± 5°C and the yam slices were dried to moisture content of 6% that was determined by weight difference. The yam flour used in this study was of less than 150 µm size.

Experimental design

Response surface methodology (RSM) was used for the experiment. A three-level, three-factor face centered composite design (Table 1) with replicates of factorial point = 1, replicates of star point = 1, center point = 6, coded distance (α) = 1 was used to get 20 design points (Table 2). The general second-order equation was used in the experimental design of this work.

\[ Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 + \epsilon \]  

where coded values \( y \), \( m \) and \( t \) represent feed composition (% yam flour), feed moisture content (%) and barrel temperature (°C) respectively. The intercept of the polynomial was represented by

| Table 1. Values of independent variables at three levels of the face centered composite design. |
|------------------------------------------|-------------------------------|-----------------------------|
| Independent Variables                  | Un-coded                     | Levels in coded form        |
| Feed composition (%)                    | y                             | -1                          |
|                                       |                               | 0                           |
|                                       |                               | +1                          |
| Feed moisture (%)                       | m                             | X:32:10                     |
|                                       |                               | X:27:15                     |
|                                       |                               | X:22:20                     |
| Barrel temperature (°C)                 | t                             | 3                           |
|                                       |                               | 14                          |
|                                       |                               | 15                          |
|                                       |                               | 90                          |
|                                       |                               | 100                         |
|                                       |                               | 110                         |

Feed composition [(50% rice grit+ 8% gram flour): maize grit: yam flour].
Where \( X \) represents (50% rice grit + 8% gram flour).
Table 2. Experimental design with coded and uncoded variables.

| S No. | Coded variables | Uncoded variables |
|-------|-----------------|-------------------|
|       | A   | B   | C   | Feed Composition (%) | Feed Moisture (%) | Temperature (°C) |
| 1     | -1  | -1  | -1  | 58:32:10              | 13               | 90              |
| 2     | 1   | -1  | -1  | 58:22:20              | 13               | 90              |
| 3     | -1  | 1   | -1  | 58:32:10              | 15               | 90              |
| 4     | 1   | 1   | -1  | 58:22:20              | 15               | 90              |
| 5     | -1  | -1  | 1   | 58:32:10              | 13               | 110             |
| 6     | 1   | -1  | 1   | 58:22:20              | 13               | 110             |
| 7     | -1  | 1   | 1   | 58:32:10              | 15               | 110             |
| 8     | 1   | 1   | 1   | 58:22:20              | 15               | 110             |
| 9     | -1  | 0   | 0   | 58:37:10              | 14               | 100             |
| 10    | 0   | -1  | 0   | 58:17:20              | 14               | 100             |
| 11    | 0   | 0   | -1  | 58:27:15              | 13               | 100             |
| 12    | 0   | 0   | 1   | 58:27:15              | 15               | 100             |
| 13    | 0   | 0   | 0   | 58:27:15              | 14               | 90              |
| 14    | 0   | 0   | 0   | 58:27:15              | 14               | 110             |
| 15    | 0   | 0   | 0   | 58:27:15              | 14               | 100             |
| 16    | 0   | 0   | 0   | 58:27:15              | 14               | 100             |
| 17    | 0   | 0   | 0   | 58:27:15              | 14               | 100             |
| 18    | 0   | 0   | 0   | 58:27:15              | 14               | 100             |
| 19    | 0   | 0   | 0   | 58:27:15              | 14               | 100             |
| 20    | 0   | 0   | 0   | 58:27:15              | 14               | 100             |

ko, linear coefficients were represented by k₁, k₂ and k₃, interaction coefficients were represented by k₁₂, k₁₃ and k₂₃ while k₁₁, k₂₂, and k₃₃ represent quadratic coefficients and ε represents random error.

Extrusion process

The compositions of feed batches are depicted in Table 2. The proportion of rice grits (50%) and gram flour (8%) were kept constant in all feed batches. The remainder 42% of the feed was made up of maize grits and yam flour. Yam flour was used to substitute maize grits. Yam flour was incorporated in the feed mix at 10%, 15%, and 20%. To adjust moisture content in the feed, the amount of water to be added was calculated. Water was added to the feed and a homogeneous mixture was obtained by mixing in a small-scale mixture (Flightier series 003, Teflon, India) for 20 min. The prepared feed mixture was filled in polyethylene bags (HDPE, 30 µm) and held in high precision (45 ± 0.1°C) incubator (Macro Scientific works, New Delhi) for 12 h to equilibrate and stabilize the moisture.

A single screw extruder (DLG 100, main motor capacity 30 KW, Jinan Shengrun Machinery Co.) was used for the extrusion process. To stabilize the preset temperature extruder was run for 30 minutes before experimenting. The extrusion process was carried out with feed rate of 4 kg h⁻¹ for easy and non-choking operation. The opening of the extruder die was 3 mm. The obtained extrudates were dried in cabinet dryer at 60 ± 5°C to the moisture content of 6% that was determined by weight difference and packed in polythene bag (HDPE, 30 µ) and stored properly at room temperature for further analysis.

Chemical analysis of raw materials

For proximate analysis of raw materials experiments were carried out in triplicate. Standard AOAC methods: (AOAC 935.29) for moisture content, (AOAC 922.06) for crude fat, (AOAC 992.23) for crude protein, (AOAC 923.03) for total ash and (AOAC 962.09) for crude fiber were used.[14] Total carbohydrate in all raw materials was calculated by deducting predetermined values of moisture, crude
fat, crude fiber, crude protein, and total ash from 100. Modified iodine-binding method was used to measure the starch content of all the raw materials.\[15\]

**Analysis of extrudate characteristics**

*Lateral expansion*: Lateral Expansion (LE) was determined by using a vernier caliper.\[16\] Ten extrude pieces were selected from the stored sample to calculate the lateral expansion and extrudate density. The diameter of each extrudate was measured at five different positions lengthwise using a vernier caliper. Percentage lateral expansion was measured using Eq. (2).

*Density*: The extrudate density (g/cm$^3$) was determined using Eq. (3) and by assuming extrudate a cylinder.\[17\] Ten pieces of the extrudate were selected randomly and the average value of mass in gram ($m$), diameter in cm ($D$) and length in cm ($l$) was reported.

**Water absorption index and water solubility index**

Water absorption index (WAI) and water solubility index (WSI) were evaluated as per the methods developed for cereals.\[18\] For 30 min at 30°C, 3 g of the milled extrudate was suspended in 30 mL water. Then, it was stirred in a centrifuge at 3000 rpm for 15 min. The supernatant obtained after centrifugation was poured in a weighed plate and dried at 105°C until the constant weight was obtained. Weight gained by gel and weight of dry supernatant was measured in a digital balance (NLB-1204, capacity 120 g, Phoenix, India). The weight of the gel obtained after removal of the supernatant per unit weight of original dry solids was calculated to get WAI. The WSI was the weight of the dry solids in the supernatant expressed as a percentage of the original weight of the sample.

**Maltose content**

Maltose content (MC) was analyzed by Di-nitrosalicylic Acid (DNS) method\[19\] for starch digestibility. Ten grams of DNS, 0.5 g sodium sulfite and 10 g sodium hydroxide were dissolved in 1 L of distilled water to get DNS reagent. Sample solution (3 mL) and DNS reagent (3 mL) were mixed and the mixture solution was heated at 90°C for 10 min to develop the red-brown color. To stabilize the color 1 mL of 40% potassium sodium tartrate solution was added to the mixture. After cooling to room temperature in a cold water bath, the absorbance of each sample was measured using UV–Vis spectrophotometer (LT-2203, wavelength range 190–1100 nm, Labtronics, India) at 765 nm. Samples were replaced with known amount of maltose to prepare a standard curve.

\[LE(\%) = \frac{(\text{diameter of the product}) - (\text{diameter of the diehole})}{\text{Diameter of the diehole}} \times 100\quad\text{(Eq. 2)}\]

\[\text{Density (g/cm}^3) = \frac{4}{\pi \times D^2 \times l}\quad\text{(Eq. 3)}\]

\[\text{WAI (g/g) = } \frac{\text{Weight gain by gel}}{\text{Dry weight of extrudate}}\quad\text{(Eq. 4)}\]

\[\text{WSI (\%) = } \frac{\text{Weight of dry solid in supernatant}}{\text{Dry weight of extrudate}} \times 100\quad\text{(Eq. 5)}\]
Data analysis and optimization

Analysis of variance (ANOVA) and multiple regressions was used to evaluate the competence of the second-order model equation for predicting the effects on product responses. A numerical multiresponse optimization technique called desirability was used for optimizing the extrusion conditions and predicting the optimum responses. The Design Expert software version 7.1.5 (STAT-EASE Inc., USA) was used in statistical analysis and optimization. Data of proximate composition were analyzed using IBM SPSS version 20 (IBM Corporation, Marlborough, MA, USA). In case of significant difference, Tukey’s HSD post hoc test was used to separate the means at a 5% level of significance.

RESULTS AND DISCUSSION

Chemical composition of raw materials

The proximate compositions of the rice grits, yam, and maize grits are given in Table 3. Depending on the type of raw materials, the proximate composition is significantly different ($p < 0.05$). Similar values are found for some of the proximate constituents of rice, maize grit, gram flour, and yam flour. Though most of the proximate constituents are similar, the variations observed might be due to several factors, such as irrigation, use and types of fertilizers, soil profile, climatic variations, stress, location of growing areas, growing conditions, and time. Total carbohydrate in the yam flour is higher than maize grit (Table 3). Starch content was found higher in yam flour than in maize grit which is analogous to studies by different researchers.

Product lateral expansion

The lateral expansion (LE) of the extrudate ranged from 118% to 145.5%. LE in the lowest level (−1), the highest level (+1) and the mid-level (0) which is the mean of six center point combinations (S No. 15–20, Table 2) of yam flour were 122%, 144%, and 121.89%, respectively. The ratio of maximum to minimum values for LE is 1.23. Coefficient estimate of the model (Table S1), fit statistics, and ANOVA of LE were studied where the quadratic model is significant ($p < 0.05$) while the lack of fit of the model is insignificant (Table 4). The following polynomial equation represented the effect on the product lateral expansion due to the independent variables:

\[
\text{LE} = 121.85 + 7.76y - 0.81m + 2.84t + 0.44ym - 0.41yt - 0.47mt + 14.91y^2 + 0.66m^2 - 3.73t^2 \ldots \text{(Eq. 6)}
\]

Yam flour addition and barrel temperature had a positive effect on LE, while moisture of the feed had a negative effect among the linear terms. None of the interaction coefficients was significant while the quadratic coefficient for yam flour addition was significantly positive and the quadratic coefficient for barrel temperature was significantly negative (Table S1). Replacing the maize grits with yam flour resulted in increase in the starch content (Table 3) that caused more expansion of the extrudates. Similarly, fiber content decreased due to the replacement of yam flour (Table 3) which might have resulted in increase in LE. Lower LE linked to fiber might be due to its dilution effect on starch that prevented gas bubbles from increasing to their full capacity resulting in a lower crisp texture of extrudates. A similar result was observed in cassava incorporated extrudate. Although the feed moisture had no significant effect on LE ($p > 0.05$) in the range used in this study, it had negative coefficient. High-feed moisture might reduce the mechanical friction and decrease the degree of cooking of starch affecting the expansion. The increase in temperature might cause more fully cooking of the proteins that acquires an increase in plasticity. This increased plasticity might increase the expansion of the extrudate with an increase in temperature. Increasing the yam flour and lowering moisture caused an increase in the LE (Figure 1). Decreasing the moisture content caused an increase in the drag force that applies extra pressure at the die and yam flour resulted in an increase in the starch content that caused more expansion of the extrudates.
Table 3. Chemical analysis of raw materials.

| Raw Materials | Moisture content (%) | Crude Fat (%, db) | Crude Protein (%, db) | Crude Fiber (%, db) | Ash Content (%, db) | Carbohydrate Content (%, db) | Starch Content (%, db) | Maltose Content (µg/g) |
|---------------|----------------------|-------------------|----------------------|---------------------|---------------------|-------------------------------|------------------------|-----------------------|
| Rice Grit     | 12.15±1.14           | 0.66±0.12         | 7.42±0.31            | 0.48±0.10           | 0.76±0.07           | 90.68±0.84                    | 85.84±2.37             | 275±4                 |
| Maize grit    | 12±1.1               | 3.65±0.35         | 10.09±0.12           | 4.22±0.21           | 1.75±0.22           | 80.29±0.76                    | 68.90±2.22             | 252.33±4.51           |
| Gram flour    | 11.6±0.89            | 5.77±0.32         | 23.34±0.74           | 1.40±0.52           | 3.21±0.15           | 66.28±1.73                    | 47.51±1.51             | 244±2                 |
| Yam flour     | 9.2±1.24             | 1.21±0.22         | 6.06±0.70            | 1.76±0.45           | 3.74±0.27           | 87.24±1.35                    | 87.03±2.63             | 259.33±5.03           |

The values in the table are the mean of the triplicates ± standard deviation. Different alphabets in the column indicates significant differences at p < 0.05.
Figure 1. Response surface plot for lateral expansion as a function of feed moisture and yam flour level at center value of temperature.

**Product density**

The density of the extrudate ranged from 0.22 to 0.29 g/cm³. The density in the lowest level (−1), the highest level (+1), and the mid-level (0) which is the mean of six center point combinations (S No. 15–20, Table 2) of yam flour were 0.28, 0.25, and 0.26 g/cm³ respectively. The ratio of maximum to minimum values for density is 1.3. F values for lack-of-fit were non-significant (p > 0.05), and coefficient of the determination was high that assures the soundness of the model fitted in experimental data (Table 4–5). The following polynomial equation represented the effect on the product density due to the independent variables:

\[
D = 0.256 - 0.008 y + 0.008 m - 0.014 t - 0.001 y m - 0.005 y t + 0.003 m t - 0.013 y^2 + 0.028 m^2 - 0.004 t^2 \quad \text{(Eq. 7)}
\]

None of the interaction coefficients were significant while all the linear coefficients were significant. The quadratic coefficient for feed moisture was significantly positive (Table S1). At low level of yam flour substitution, higher fiber content in the feed mixture from the maize decreased the density of extrudate (Table 3 and Table S1) which is similar to earlier reports.\(^{[17,29]}\) The density of extrudates was significantly (p < 0.05) affected by feed moisture (Table S1). High moisture content in the feed caused increased density and this might be the result of cooking of starch and decrease of melt elasticity.\(^{[30]}\) Bulk density decreased as barrel temperature increased, which is similar to past researches.\(^{[30,31]}\) Increased barrel temperature provides more energy to evaporate superheated water of extrudates while leaving the die. With increased temperatures, the extrudates leaving the die become lighter due to higher loss of water.\(^{[32]}\) Density decreases significantly with an interaction effect of yam flour addition and temperature (Figure 2). Higher temperature leading to moisture loss and more fiber in the feed by adding less fiber contained yam flour might have reduced the density of the product.

**Water solubility index**

The water solubility (WSI) of the extrudate ranged from 6.9% to 7.6%. The WSI in the lowest level (−1), the highest level (+1), and the mid-level (0) which is the mean of six center point combinations (S No. 15–20, Table 2) of yam flour were 7.39%, 6.95%, and 7.24%, respectively. The ratio of maximum to minimum values for WSI is 1.1. Coefficient estimate of the model (Table S1), fit statistics and ANOVA of WSI were studied where the quadratic model is significant, while the lack of fit of the model is insignificant (Table 4). The linear coefficient for yam flour addition and the interactive coefficient for yam flour (%) were significant and the quadratic coefficients for feed moisture and
The following polynomial equation represented the effect on the water solubility index due to the independent variables:

\[ \text{WSI} = 7.289 - 0.112 y - 0.013 m - 0.062 t + 0.047 y m + 0.102 y t - 0.036 m t - 0.101 y^2 - 0.248 m^2 + 0.231 t^2 \]  

Table 4. Analysis of variance (ANOVA) results for fitted models.

| Response                          | Source        | Sum of squares | Df | Mean squares | F-value | p-value |
|-----------------------------------|---------------|----------------|----|--------------|---------|---------|
| Lateral expansion (%)            | Regression    | 1586.743       | 9  | 176.305      | 45.554  | < 0.0001*|
|                                  | Lack of fit   | 20.676         | 5  | 4.135        | 1.147   | 0.4420  |
|                                  | Pure error    | 18.026         | 5  | 3.605        |         |         |
|                                  | Residual      | 38.702         | 10 | 3.870        |         |         |
|                                  | Total         | 1625.446       | 19 |              |         |         |
|                                  | R-Squared     | 0.976          |     |              |         |         |
|                                  | Adjusted R²   | 0.955          |     |              |         |         |
|                                  | Adeq. Precision | 21.147       |     |              |         |         |
| Density (g/cm³)                  | Regression    | 0.0059         | 9  | 0.00066      | 5.120   | 0.0088* |
|                                  | Lack of fit   | 0.0010         | 5  | 0.00021      | 4.164   | 0.0718  |
|                                  | Pure error    | 0.0002         | 5  | 0.00005      |         |         |
|                                  | Residual      | 0.0013         | 10 | 0.00013      |         |         |
|                                  | Total         | 0.0072         | 19 |              |         |         |
|                                  | R²-value      | 0.8217         |     |              |         |         |
|                                  | Adjusted R²   | 0.6612         |     |              |         |         |
|                                  | Adeq. Precision | 7.8464         |     |              |         |         |
| Water solubility index (%)       | Regression    | 0.593          | 9  | 0.066        | 4.72    | 0.0118* |
|                                  | Lack of fit   | 0.109          | 5  | 0.022        | 3.62    | 0.0919  |
|                                  | Pure error    | 0.030          | 5  | 0.006        |         |         |
|                                  | Residual      | 0.140          | 10 | 0.014        |         |         |
|                                  | Total         | 0.733          | 19 |              |         |         |
|                                  | R²-value      | 0.809          |     |              |         |         |
|                                  | Adjusted R²   | 0.638          |     |              |         |         |
|                                  | Adeq. Precision | 7.140          |     |              |         |         |
| Water absorption index (g/g)     | Regression    | 0.483          | 9  | 0.0537       | 5.471   | 0.0069* |
|                                  | Lack of fit   | 0.068          | 5  | 0.0136       | 2.247   | 0.1975  |
|                                  | Pure error    | 0.030          | 5  | 0.0060       |         |         |
|                                  | Residual      | 0.098          | 10 | 0.0098       |         |         |
|                                  | Total         | 0.581          | 19 |              |         |         |
|                                  | R²-value      | 0.831          |     |              |         |         |
|                                  | Adjusted R²   | 0.679          |     |              |         |         |
|                                  | Adeq. Precision | 8.352          |     |              |         |         |
| Maltose content (µg/g)           | Regression    | 7070.227       | 9  | 785.581      | 45.214  | < 0.0001*|
|                                  | Lack of fit   | 93.787         | 5  | 18.757       | 1.173   | 0.4327  |
|                                  | Pure error    | 79.959         | 5  | 15.992       |         |         |
|                                  | Residual      | 173.746        | 10 | 17.375       |         |         |
|                                  | Total         | 7243.973       | 19 |              |         |         |
|                                  | R²-value      | 0.976          |     |              |         |         |
|                                  | Adjusted R²   | 0.954          |     |              |         |         |
|                                  | Adeq. Precision | 21.060         |     |              |         |         |

*Significant at p < 0.05, df = degree of freedom

Table 5. Numeric multi response optimization constraints of extrudates with yam flour.

| Name                              | Goal     | Lower Limit | Upper Limit | Lower weight | Upper weight | Importance |
|-----------------------------------|----------|-------------|-------------|--------------|--------------|------------|
| Yam flour (%)                     | maximize | 10          | 20          | 1            | 1            | 5          |
| Feed moisture (%)                 | is in range | 13          | 15          | 1            | 1            | 3          |
| Temperature (°C)                  | is in range | 90          | 110         | 1            | 1            | 3          |
| Lateral expansion (%)             | maximize | 118         | 145.5       | 1            | 1            | 5          |
| Density (g/cm³)                   | minimize | 0.222       | 0.29        | 1            | 1            | 5          |
| WAI (g/g)                         | minimize | 5.78        | 6.4         | 1            | 1            | 3          |
| WSI (%)                           | maximize | 6.9         | 7.6         | 1            | 1            | 3          |
| Maltose content (µg/g)            | maximize | 248.98      | 307         | 1            | 1            | 3          |
Figure 2. Response surface plot for density as a function of barrel temperature and yam flour level at center value of feed moisture.

An increase of yam flour in the feed mixture significantly decreased the WSI of the extrudate which may be attributed to the degradation of the fiber constituents.\textsuperscript{[33]} Maize having more fiber than yam (Table 3), and the presence of maize interrupts the persistent structure of feed melt in the extruder, obstructing elastic distortion during extrusion.\textsuperscript{[34]} An increase of moisture in the feed mixture significantly reduced WSI which is alike of earlier research in rice based extrudates\textsuperscript{[17]} . Lower feed moisture might result in higher shear degradation of starch, which can increase WSI. Although the linear effect of WSI and temperature is negative\textsuperscript{[35]}, the interactive effect of temperature and yam flour in feed had a positive effect in WSI (Figure 3).

**Water absorption index**

The water absorption index (WAI) ranged from 5.78 to 6.4 g/g for the extrudate. The WAI in the lowest level (−1), the highest level (+1), and the mid-level (0) which is mean of six center point combinations (S

Figure 3. Response surface plot for water solubility index as a function of barrel temperature and yam flour level at center value of feed moisture.
No. 15–20, Table 2) of yam flour were 6.19, 5.83, and 6.04, respectively. The ratio of maximum to minimum values for WAI is 1.1. Coefficient estimate of the model (Table S1), fit statistics, and ANOVA of WAI were studied where the quadratic model is significant, while the lack of fit of the model is insignificant (Table 4). None of the interaction coefficients was significant while the linear coefficients for yam flour addition and barrel temperature was significant. The quadratic coefficient for feed moisture and barrel temperature was significant (Table S1). The following polynomial equation represented the effect on the water absorption index due to the independent variables:

\[
WAI = 6.083 - 0.008 y + 0.008 m - 0.014 t - 0.001 y m - 0.005 y t + 0.003 m t - 0.013 y^2 + 0.028 m^2 - 0.004 t^2
\]

Increasing moisture and decreasing yam flour proportion in the feed blend resulted in increase of WAI values in the extrudates (Figure 4). An increase in feed moisture causes more cooking of starch or gelatinization and more fragmentation of starch in the extrusion process.\(^{[36,37]}\) The degradation of starch due to the increased temperature might result in a decrease in WAI values of the extrudate.\(^{[38]}\) Dextrinization may overshadow the gelatinization of the starch at increased temperature and thus WAI may decrease.\(^{[17]}\) Increasing yam flour in the feed blend will drop the WAI of the product. Addition of yam flour decreased the total protein content of feed blend (Table 3). This could be the reason in decrease of WAI. Identical effects were reported in former research.\(^{[39]}\)

**Maltose content**

The maltose content (MC) ranged from 248.98 to 307 μg/g for the extrudate. The MC in the lowest level (−2), the highest level (+2), and the mid-level (0), which is the mean of six center point combinations (S No. 25–30, Table 2) of yam flour were 257.42, 303.8, and 255.65 μg/g, respectively. The ratio of maximum to minimum values for MC is 1.23. Coefficient estimate of the model (Table 4), fit statistics, and ANOVA of MC were studied, where the quadratic model is significant while the lack of fit of the model is insignificant (Table 4). None of the interaction coefficients were significant while the linear coefficients for yam flour addition and barrel temperature was significant. The quadratic coefficient for yam flour addition and barrel temperature was also significant (Table S1). The following polynomial equation represented the effect on the maltose content due to the independent variables:

\[
MC = 257.07 + 16.39 y - 1.76 m + 6.02 t + 0.977 y m - 0.887 y t - 0.912 m t + 31.44 y^2 + 1.37 m^2 - 7.91 t^2
\]

An increase in the yam flour raises the presence of starch that directly increases maltose content. Higher incorporation of yam flour caused more gelatinized extrudates, which is assisted by the

![Figure 4](image-url)  
*Figure 4.* Response surface plot for water absorption index as a function of feed moisture and yam flour level at center value of barrel temperature.
tendency of expansion ratio due to yam addition. Maltose content increased with an increase in temperature and proportion of yam flour in the feed composition. During the cooking of starch, more cleavage in the long chains of starch ultimately might have resulted in formation of shorter chains due to increased temperature. The combined effect of yam addition and feed moisture showed a positive effect on starch, which might be due to the higher effect of yam causing more gelatinization, though moisture had the dilution effect (Figure 5).

**Optimization and verification**

A numeric, multi-response optimization technique was used by statistical software (Design-Expert, version 7.5.1, Stat-Ease, Inc.). The main criteria for optimizing extrusion conditions were maximum LE, WSI, and maltose content, minimum density, and WAI (Table 6). To optimize the process conditions, an importance value of 5 for yam flour addition, and 3 was given to all remaining process parameters. Similarly, an importance value of 5 was given for LE and density while other responses were given an importance value of 3. The optimum operating conditions for yam flour addition, feed moisture and barrel temperature were 20%, 13.28%, and 108.83°C, respectively. For these optimized extrusion conditions, the predicted values for the responses were 144.65% for LE, 0.222 g/cm³ for the density, 6.002 g/g for WAI, 7.217% for WSI, and 305.15 µg/g for maltose content with desirability 0.848. In order to verify the predicted responses of extrudates under optimized extrusion conditions, an experiment was carried out where percentage deviation from predicted values to actual values for the different responses ranged from 2.08% to 13.36% (Table 6).

**Table 6.** Predicted and actual values of the responses at the optimized condition

| Responses               | Predicted values | Actual values | % deviation from predicted value |
|-------------------------|------------------|---------------|---------------------------------|
| Lateral expansion (%)   | 144.65           | 157.3         | 8.75                            |
| Bulk density (g/cm³)    | 0.222            | 0.21          | 5.41                            |
| WSI (%)                 | 7.217            | 7.8           | 8.08                            |
| WAI (g/g)               | 6.002            | 5.2           | 13.36                           |
| Maltose content (µg/g)  | 305.15           | 298.8         | 2.08                            |
CONCLUSION

Increasing the proportion of yam flour in the feed and higher barrel temperatures resulted in increased expansion of extrudate. Decreasing the moisture in the feed led to an increase in LE and a decrease in density. The physical properties of the extrudates were significantly affected by extrusion conditions and the addition of yam flour. Thus, due to the high starch content of yam and positive impact on extrudate characteristics, yam has the potential to substitute maize in existing feed composition and suggesting the possibility of using yam flour in preparing expanded extrudates.

Acknowledgments

The authors are thankful to CG Foods, Nawalparasi, Nepal for providing raw materials and processing facilities for carrying out the experiments. Authors declare no any conflict of interest.

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Conflicts of Interest

The authors declare no conflicts of interest.

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