Twin Screw Extrusion Cooking of Lotus Rhizome and Broken Rice Flour Blends: A Response Surface Analysis

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Lotus rhizome supplementation increases the fibre content of starch based expanded snacks. Therefore, a systematic study was conducted for optimizing the blending level of Lotus rhizomes and broken rice flour for the production of expanded snacks through co-rotating twin screw extruder. Response surface methodology was used to study the effects of feed composition, feed moisture, screw speed and barrel temperature on specific mechanical energy, bulk density, water absorption index, water solubility index, expansion ratio and breaking strength whose values varied from 41.08 to 88.95 Wh/kg, 101 to 613 Kg/m$^3$, 2.68 to 7.05 g/g, 4.54 to 8.41%, 1.76 to 3.98 and 61.6 to 212 N respectively. Response surface regression models were established to determine the responses as functions of process variables. Regression models for all the responses were highly significant (p<0.01) with high co-efficient of determination ($R^2$ > 0.95). The compromised optimum conditions obtained by numerical optimization for development of extruded snacks were lotus rhizome flour to broken rice flour ratio (40:60), moisture content 15%, screw speed 500 rpm and die temperature 170$^\circ$C. This paper therefore explores the optimization of processing conditions for the development fibre rich extruded food from lotus rhizome and broken rice flour blends.

Keywords: Lotus Rhizome, Twin Screw, Water Absorption Index (WAI)

Introduction

Lotus rhizomes exhibit nutritional and medicinal properties and are used as popular vegetables or eaten in roasted, pickle dried and fried forms. A careful survey of literature showed that the work has been done earlier on proximate composition, functional properties, phytochemical analysis and antioxidant activities of lotus rhizomes. However, no data has been found to be published regarding the extrusion processing of lotus rhizomes. Extruded products are generally made from starch based raw materials e.g. cereal grains. Broken rice, a by product of milling process has nutritive value similar to whole rice, is readily available at relatively cheaper rates and thus could be used as an attractive ingredient in extrusion industry. Therefore, the aim of the present study was to investigate the influence of extrusion process variables on physical properties of lotus rhizome incorporated rice based extrudates using response surface methodology and to establish regression models to predict the product responses as a function of the process variables.

Materials and methods

A widely cultivated paddy variety (Jhelum) obtained from Mountain research Station for field crops, Khudwani, Anantnag, Sher-e-Kashmir University of Agricultural Sciences & Technology of Kashmir, India was shelled using Satake rice mill (Satake, Hiroshima, Japan). The brown rice thus obtained was passed through rice polisher. The small rice brokens ($<1/8$th of actual kernel size) and locally procured lotus rhizomes were ground in a lab mill model 3303 (Perten, Hagersten Sweden) to a fineness that passed through a 200 µm sieve. Proximate analysis of flour and final product. The raw materials were subjected to proximate composition analysis using following standard AACC methods.

- Moisture: Oven drying at 103 $^\circ$C
- Protein: Micro Kjeldahl (N×6.25)
- Fat: Defatting in a Soxhlet apparatus with petroleum ether
- Starch: Using Fehling’s Solution
- Ash: Calcination at 550$^\circ$C
- Crude Fibre: Using Fibre tech (Foss Instrument Denmark)
- Energy value: Using Bomb calorimeter (Model 6050, Parr instruments, USA)
- Carbohydrate: by difference method.

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Extrusion process
Extrusion was performed in a co-rotating, intermeshing twin screw extruder Model BC21 (Clextral BC-21, Firminy, France), consisting of four independent zones of controlled temperature in the barrel. The barrel diameter and its length to diameter ratio (L/D) were 2.5 mm and 16:1 respectively. Temperature of the first, second and third zone were maintained at 40, 60, and 90 °C respectively throughout the experiment, while the temperature of the last zone (compression and die section) was varied accordingly to the experimental design. The diameter of die opening was 3 mm. Raw material was metered into the extruder with a single screw volumetric feeder (D.S and M, Modena, Italy). The moisture content of feed was varied by injecting water (approximately 50°C) into extruder with water pump. A variable speed die face cutter with four bladed knives was used to cut the extrudates.

Experimental design
Extrusion is a complex process involving many variables, among them barrel temperature, screw speed and feed moisture are the most important factors. A central composite rotatable design (CCRD)^3 was used to incorporate these three variables and lotus rhizome incorporation. The CCRD-coded levels and experiment ranges of the four independent variables are shown in Table 1 these were selected based on preliminary trials. Experiments were randomized in order to minimize the systematic bias in observed responses due to extraneous factors. Both

<table>
<thead>
<tr>
<th>Composition (%)</th>
<th>Moisture (%)</th>
<th>Screw speed (rpm)</th>
<th>Barrel Temp. (°C)</th>
<th>SME (Wh/kg)</th>
<th>BD (kg/m^3)</th>
<th>WAI (g/g)</th>
<th>WSI (%)</th>
<th>ER</th>
<th>BS (N)</th>
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<td>300 (-1)</td>
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<td>4.94</td>
<td>6.75</td>
<td>2.43</td>
<td>124.10</td>
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SME (Wh/kg) = Specific mechanical energy; BD (kg/m^3) = bulk density; WAI (g/g) = Water absorption index; WSI (%) = Water solubility index; ER = Expansion ratio; BS (N) = breaking strength
individual effects and interactive effects of independent variables on product responses were determined. All the extrusion experiments were repeated twice.

**Determination of system response**

**Specific mechanical energy**
Specific mechanical energy (SME) was calculated as Wh/kg using standard equation 4.

**Determination of product responses**

**Bulk density**
Bulk density (BD) was measured using displacement method 5.

**Water absorption and solubility indices**
Water absorption index (WAI) and water solubility index (WSI) of extruded products were determined by modification of the method 6.

**Expansion ratio**
To determine the expansion ratio (ER), the cross-sectional diameter of the extrudates was measured with a digital Vernier caliper. The ratio of diameter of extrudate and the diameter of die was used to express the expansion of extrudate 7. The ER values were obtained from 15 random samples for each extrusion condition.

**Breaking strength**
Breaking strength was measured using TA-XT 2i texture analyzer (stable micro systems, survey, UK). A three point breaking test 8 was used to measure the maximum force required to break the extrudate samples. Average values were recorded after ten replications.

**Data analysis and process optimization using response surface methodology**
Response surface methodology (RSM) is a statistical method used to describe the relationship between process variables and product quality characteristics. It is typically used for mapping a response surface over a particular region of interest, optimizing the response, or for selecting operating conditions to achieve target specifications or customer requirements. Second order polynomial regression models were established for the dependent variables to fit experimental data for each response using statistical software Design-Expert 9 (Stat-Ease Inc, Minneapolis, MN, USA). Data was analyzed by multiple regression analysis and statistical significance of the terms was examined by analysis of variance (ANOVA) for each response. The adequacy of regression model was checked by correlation coefficients. The lack of fit test was used to judge the adequacy of model fit. To aid visualization of variation in responses with respect to process variables, series of three dimensional response surface plots were drawn. The optimization was carried out under following constraints: maximize SME, WAI, WSI, and ER; minimize BD and Breaking Strength.

**Consumer acceptance test**
A consumer panel of 400 un-trained judges evaluated the acceptability of the optimized product in terms of colour, flavor, texture, appearance and overall acceptability using 4 point scale (poor = 1, fair = 2, good = 3, excellent = 4). All the samples were randomized using 3 digit codes. The test panelists were 200 male and 200 female adults (> 18 years of age) from district Srinagar, Jammu and Kashmir, India.

**Result and Discussion**
The proximate analysis of raw materials revealed that the percentage of moisture, protein, fat, ash, fibre, carbohydrate and starch were 12.92, 8.09, 0.23, 0.47, 0.78, 77.51, 68.90 in rice flour and 5.90, 8.24, 2.72, 1.33, 10.80, 71.01 and 53.37 in lotus rhizome flour respectively. The fibre content in lotus rhizome flour was about 13.85 times higher than that of rice flour. Since the high fibrous extruded snacks are not available in the market; there is an increasing interest in enhancing the fibre content of such products. Therefore the lotus rhizome can be explored for development of fibre rich extruded products. The data on mean values of system and product responses are summarized in Table 1. Analysis of variance is summarized in Table 2. Models for all parameters were highly significant (p<0.01) with high coefficient of determination (R\(^2\) > 0.95). Thus, models developed could be used to navigate the design space and to predict the responses correctly. The predicted R-square was found in reasonable agreement with adjusted R-square for all the parameters. Coefficient of variation being less than 6.6% suggests that the experiments were reasonably accurate and models are reproducible. Adequate precision compares the range of predicted values at the design points to average the prediction error. The adequate precision value of > 4 indicates adequate model discrimination. All the parameters showed highly desirable adequate precision Table 2. None of the models showed
significant lack of fit, indicating that all second order polynomial models correlated well with the measured data. Further the p-values reflected that all the models were significant. Significant effects of extrusion variables on product characteristics have been reported in previous studies as well\textsuperscript{9,10, 11}.

**System response**

*Specific mechanical energy*

SME is the energy provided by motor drive per unit mass of the material in the extruder\textsuperscript{12}. The amount of mechanical energy delivered to the extruded material plays an important role in starch conversion. Higher SME usually results in greater degree of starch gelatinization and extrudate expansion. The SME values observed in this experiment ranged between 41.08 to 88.95 Wh/kg. Table 1 The fitted model for SME shown below in equation 1 indicates the linear effects with composition (A), moisture (B), screw speed (C) and quadratic effect with barrel temperature (D).

\[
\text{SME} = 80.73 - 1.57A - 3.43B + 4.50C - 4.77D^2 \quad \ldots (1)
\]

Figure 1 shows the response surface plot of SME vs two independent variables at a time with third taken at mid point. The negative coefficients of linear terms of composition and moisture indicate that SME decreases with the increase in these variables, while as positive coefficient for screw speed indicates that SME increases with the increase in screw speed. The barrel temperature had a significant (p<0.01) quadratic negative effect on SME. Increase in feed moisture and barrel temperature reduces melt viscosity and hence SME. Increase in SME with the increase in screw speed was possibly due to high shear rate. Slight decrease in SME with the addition of lotus rhizomes could be attributed to high fat and fibre content of lotus rhizome. Similar results have been reported in extrusion processing of whole quinoa (\textit{Chenopodium quinoa})\textsuperscript{13} and in wheat (\textit{Triticum aestivium}), corn (\textit{Zea mays}) and barley (\textit{Hordeum vulgare}) extrudate\textsuperscript{14}.

**Table 2 — Analysis of variance for the fit of experimental data to response surface models**

<table>
<thead>
<tr>
<th>Regression</th>
<th>SME</th>
<th>BD</th>
<th>WAI</th>
<th>WSI</th>
<th>ER</th>
<th>BS</th>
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</thead>
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<td>0.9956</td>
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</table>

Fig. 1 — Response surface plots of system parameter vs two independent variables at a time.
Product responses

Bulk density

Bulk density is very important parameter of extruded products, which measures the expansion that has occurred as a result of extrusion. Expansion ratio considers expansion only in direction perpendicular to extrudate flow, whereas unit in bulk density considers expansion in all directions\(^7\). In the present study, the bulk density was found in the range of 101 to 613 Kg/m\(^3\) Table 1. The regression equation for bulk density depicted below in equation 2 demonstrate the quadratic effect with moisture, linear effects with all the four independent variables and interactive effect with moisture content and screw speed.

\[
BD = 164 + 52.37A + 43.2 B - 37.04C - 42.02D + 16.56 BC + 80.21B^2 \tag{2}
\]

The response surface plot depicted in Figure 2 shows that lotus rhizome incorporation and feed moisture had positive effects while the barrel...
temperature and screw speed had negative effects on BD. The positive effect of feed moisture on BD would reflect its influence on elastic characteristics of starch based material. Higher feed moisture during extrusion reduces the elasticity of the doughy through plastization of melt, resulting in reduced SME which decreases the expansion and increases the bulk density of extrudates\textsuperscript{11}. The decrease in bulk density with the increase in screw speed and barrel temperature was probably due to higher gelatinization of starch. As the gelatinization increases the volume of extruded products increases and bulk density decreases. When extrudate exits from the die, at high barrel temperature, a part of moisture quickly flash off as steam and results in an expanded structure with large alveoli and low density. The significant positive (p<0.01) effect of lotus rhizome incorporation on bulk density could be attributed to higher fat or fibre content of lotus rhizome which affects the process of gelatinization and thus rheological properties of the melted material in extruder. The significant positive interaction of moisture and screw speed suggested that effect of moisture content on bulk density was dominant over that of screw speed. This was in concomitance with the previous findings reported in rice based extrudates\textsuperscript{15} and in potato based extruded snacks\textsuperscript{11}.

Water absorption index

Water absorption index measures the water holding by the starch after swelling in excess water\textsuperscript{16} which corresponds to weight of gel formed. WAI depends on the availability of hydrophilic groups and on the capacity of gel formation of the macromolecules\textsuperscript{17}. In the present study the WAI of extrudates varied between 2.68 to 7.05 g/g based on the level of extrusion variable Table 1. The fitted regression model for WAI shown in equation 3 demonstrating linear effect with composition (A), moisture (B) and screw speed (C).

\[
\text{WAI} = 4.92 - 0.70A + 0.69B - 0.24C \quad \text{... (3)}
\]

The response surface plots shown in Figure 2 demonstrates that WAI increased with the increase in feed moisture and decreased with the increase in composition and screw speed. The significant (p<0.01) positive effect of feed moisture may be due to low viscosity of starch at high moisture allowing the extensive internal mixing and uniform heating which would account for enhanced gelatinization of starch\textsuperscript{18}. Decreasing effect of lotus rhizome incorporation on WAI may be attributed to its lower starch and higher fibre content than rice which may affect the extent of starch gelatinization in extruder and therefore, reduces the water absorption. The significant negative effect of screw speed on WAI may be due to more undamaged polymer chain and greater availability of hydrophilic groups under low shear conditions at lower screw speed. The undamaged polymer chains and hydrophilic groups could bind more water and therefore results in higher WAI. Similar effects have been previously also reported in extrusion studies in millet – legume blends\textsuperscript{19} and rice grits and partially defatted hazelnut flour blends\textsuperscript{18}.

Water solubility index

WSI is in-vitro indicator of starch digestibility which measures the amount of soluble components released from starch during extrusion processing. WSI values for the extrudates ranged between 4.54 to 8.41 percent Table 1. The fitted regression model for WSI shown in equation 4 demonstrating the linear effect with all the four independent variables, quadratic with composition and moisture and interactive with composition (A) and moisture (B).

\[
\text{WSI} = 6.75 + 0.33A - 0.28B + 0.13C + 0.12D + 0.07AB + 0.15A^2 - 0.42B^2 \quad \text{... (4)}
\]

The response surface plots also Figure 2 demonstrate the negative influence of moisture and positive influence of composition, screw speed and barrel temperature on WSI. Extrusion at low moisture could result in increase in water soluble molecules\textsuperscript{20}. Similar effects have been reported in other extrusion related studies as well\textsuperscript{18, 21}. The increase in WSI with the increase in lotus rhizome incorporation level was possibly due to its higher water solubility compared to rice. Similar results were reported in soya protein fortified extrudates\textsuperscript{22}. The significant (p<0.01) positive interactive effect of composition and feed moisture suggests the dominating effect of composition over that of moisture. Higher WSI of extrudates with the increasing screw speed may be related to increase in SME. The high mechanical shear causes breakdown of macromolecules to small molecules with higher solubility. High barrel temperature would increase the degree of starch gelatinization, thus increase the soluble starch components which results in increase in WSI. The
increase in WSI with the increase in screw speed and barrel temperature was in concomitance with the results reported in extrusion processing of Yam flour, quinoa and potato based snacks.

Expansion ratio

When extrudate melts exits the die, sudden pressure drop causes flash-off of internal moisture which nucleates to form bubbles in molten extrudates allowing expansion of the melt. The fitted model for ER is shown in equation 5 indicating linear effects with all the four independent variables and quadratic effect with only screw speed (C). ER of extrudates was found in the range of 1.76 to 3.98. Table 1.

\[ \text{ER} = 2.46 - 0.22A - 0.12B + 0.28C + 0.39D + 0.30C^2 \]  
\[ \ldots (5) \]

The surface plots shown in Figure 2 demonstrating that composition and moisture had negative effects, while screw and barrel temperature had positive effects on ER. Increase in moisture content during extrusion would change the molecular structure of amyllopectin in starch based material, reducing the melt elasticity and thus decreases the radial expansion. The decreasing effect of lotus rhizome on ER may be attributed to dilution effect of lotus rhizome on the starch content of blend due to high fibre content in lotus stem. During the extrusion processing, fibre tend to remain firm and stable, without size reduction, which cause reduction in expansion ratio. Further the fibre may bind water more strongly than protein and starch during extrusion. This water binding capacity inhibits water loss at the die, thus reduces the expansion. The increasing effect of barrel temperature on expansion ratio could be probably due to more gelatinization of starch at high temperature. Low screw speed (in other way more residence time in extruder) might have induced degradation of amyllopectin networks in the material that changed the melt elasticity characteristics and reduced the expansion ratio. The results of the present study are in concordance with findings reported in twin screw extrusion cooking of rice flour and blend of corn flour and soya protein isolate.

Breaking strength

Breaking strength of expanded extrudates is associated with expansion and cell structure of the product. In the present study, breaking strength was measured as the peak force required for a probe to penetrate the extrudate. Mean value of breaking strength were found in the range of 61.6 to 212 N Table 1. The fitted regression model for breaking strength is shown in equation 6 demonstrating the linear effects with composition (A), screw speed (C) and barrel temperature (D).

\[ \text{BS} = 125.10 + 10.10A - 23.02C - 17.04D \]  
\[ \ldots (6) \]

Figure 2 shows the response surface plot of breaking strength vs two independent variables at a time with third taken at the midpoint level. The increasing effect of composition (i.e lotus rhizome incorporation level) on breaking strength as found in this study could be attributed to reduced expansion due to high fat and fibre content of lotus rhizome. This output is in agreement with the finding reported for soy protein fortified extrudates. Breaking strength decreased with the increase in screw speed and temperature. It is expected that increasing temperature as well as screw speed would decrease melt viscosity, which favour the bubble growth and produce low density product with small and thin cells, therefore increase the crispness of the extrudates. A low density product naturally offers lower breaking strength. Similar trends have been previously reported in barley-tomato pomace blended extrudates, corn, barley and chickpea based extrudates.

Optimization and validation

The highest desirability value for obtaining optimum conditions in extrusion processing of broken rice and lotus rhizome flour was 0.748 Figure 3. The optimum conditions obtained for development of extrudates were lotus rhizome level 40%, feed moisture 15%, screw speed 500 rpm and barrel temperature 170\(^\circ\) C. The predicted response values and the actual obtained response values were almost similar. It can be noted from Table 3 that the variations of actual response values were within 4% of the predicted values. The extruded product prepared by using optimized conditions was analyzed for proximate composition. The moisture content of the product was found to be 4.2%, protein 8.2%, fat 0.48%, ash 0.98%, fibre 2.8%, carbohydrate 83.32% and calorific value of 370.40 Kcal/100g . The average consumer acceptability score was 4.0 (excellent) on a 4-point scale, when the product was subjected to consumer acceptability test (n=400).
Conclusion

Overall response surface methodology revealed the significant effects of all the four independent variables (composition, feed moisture, screw speed and barrel temperature) on system and product responses. All the models were statistically valid and provided adequate information regarding the behaviour of the responses upon variation in processing variables. The optimum lotus rhizome level, moisture content, screw speed and barrel temperature estimated by response surface of desirability function for the production of lotus stem incorporated rice based extruded snacks were 40%, 15%, 500rpm and 170°C respectively. The present study confirms the feasibility of developing fibre rich extruded snacks food from lotus rhizomes. Large scale production of these products could result in profitable utilization of this underutilized crop and will help to provide remunerative returns to the habitations residing on the periphery of water bodies, who are directly or indirectly involved in its trade.

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