Physical Properties of Refabricated Rice as Affected by Extrusion: A Response Surface Analysis

Syed Zameer Hussain and Baljit Singh

ABSTRACT

The aim of this study was to optimize the extrusion conditions for production of refabricated rice using a response surface modeling approach. The effects of feed moisture content, screw speed, and barrel temperature on the physical properties of rice grains refabricated using a corotating twin-screw extruder were investigated. Rice flour (variety PR-116) obtained from broken grains (smaller than one-eighth of a whole grain) was used in the study. Screw speeds at five levels between 49 and 150 rpm, barrel temperatures between 59 and 110°C, and feed moisture contents between 31 and 45% were tested. All of the physical properties of the refabricated rice grains that were evaluated (thousand kernel weight, length/breadth ratio, bulk density, and breaking strength) were significantly (P < 0.01) affected by these three process variables. Response surface regression models were established to correlate the physical properties of refabricated rice grains to the process variables. Understanding the effects of process variables on the physical properties and optimization of extrusion conditions was deemed useful for the development of high-quality refabricated rice.

Extrusion technology has been available commercially in the food industry for nearly a century (10). Starch-based food ingredients such as corn, rice, and semolina are ideal candidates for extrusion processing (6). During extrusion, the shearing stress and heat produced by dissipation of mechanical energy or direct heating of the dough cause quick cooking that determines the characteristics of the final product. Changes in the biopolymers (2,12). In particular, the biopolymers in the dough are subjected to changes in their structure (e.g., gelatinization and dextrinization of starch and denaturation, realignment, and cross-linking of proteins, as well as other changes) (11). At the end of extrusion cooking, the viscoelastic material that has been formed is forced through a die, and the sudden drop in pressure causes instantaneous evaporation of water from the material, leading to a product with an expanded and porous structure. The degree of expansion is influenced primarily by the moisture content of the dough and barrel temperature (3). Extrusion cooking is an ideal method for manufacturing a variety of food products that range from snacks and breakfast cereals to baby foods. However, because it is a complex multivariate process, careful control of extrusion parameters is required to maintain product quality. There are many areas in extrusion processing that require further research, and production of nonexpanded extruded products is one such area. Very little has been published on the effects of extrusion on the physical properties of nonexpanded products.

Broken rice, a by-product of the milling process, has a nutritive value similar to head rice and is readily available at a lower cost. Utilization of broken rice for the development of nonexpanded refabricated rice is of great interest. The literature contains little information on the effects of extrusion conditions on the physical properties of refabricated rice. Therefore, the objectives of the current study were 1) to investigate the influence of extrusion process variables on the physical properties of refabricated rice and optimize processing conditions for the production of refabricated rice; and 2) to devise regression models to predict the physical properties of refabricated rice as a function of process variables. This study extends our previous work on the effects of extrusion conditions on the pasting behavior and microstructure of refabricated rice (18). Because physical properties are key components of customer acceptance, this study will be useful for optimizing extrusion conditions for production of refabricated rice with suitable end-use qualities.

MATERIALS AND METHODS

Paddy variety PR-116 was obtained from the Department of Plant Breeding and Genetics, Punjab Agricultural University, Ludhiana, Punjab, India, and shelled using a rice mill (Satake Corporation) to obtain brown rice, which in turn was passed through a rice polisher. The small broken pieces (smaller than one-eighth of a whole rice grain) were ground in a lab mill (model 3303, Perten Instruments) to a particle size fine enough to pass through a 200 µm sieve. The moisture content of the flour was determined as per the procedure described in AACC International Approved Method 44-01.01 (1), and an appropriate amount of water was added to adjust the flour moisture content to meet the requirements of the experimental design. Extruded refabricated rice grains were collected on stainless-steel, mesh trays. The trays were loaded into a tray dryer (NSW-154, Narang Scientific Works Pvt. Ltd.) containing a small fan and 220 V heating unit (Thermolyne, Thermo Scientific) that circulated air from the bottom to the top of the cabinet. The refabricated rice grains were predried for 2–2.5 hr at 70°C. Next, the partially dried extruded rice was stacked in trays and placed in a conditioning chamber for 8 hr for final drying at 60–70°C until the refabricated grain reached a water content of ≈10–12 g/100 g. Dried samples were stored in air-tight plastic containers at room temperature and used for analysis.

Extruder and Processing Conditions

Extrusion was performed using a corotating and intermeshing twin-screw extruder (model BC 21, Clextral). The barrel diameter was 2.5 mm, and the length/diameter ratio was 16:1. The extruder had four barrel zones. Temperatures in the first, second, and third zones were maintained at 20, 30, and 40°C, respectively, throughout the experiments, while the temperature in the last zone (compression and die section) was varied according to the experimental design. The extruder was equipped with a torque indicator, which showed torque in
proportion to the current drawn by the drive motor. Raw material was metered into the extruder with a single-screw volumetric feeder (DS & M). The extruder was calibrated carefully with respect to the combinations of feed rate and screw speed used in the experiment. Feed rate was varied for optimal filling of the extruder barrel corresponding to different screw speeds. The moisture content of the feed material was varied by injecting water into the extruder with a water pump. A prestandardized cutter with four bladed knives and a die (8 × 1.5 mm) made of stainless steel was used to shape the refabricated rice grains.

**Experimental Design**

Extrusion is a complex process that involves many variables. Among them, barrel temperature, screw speed, and feed moisture content are critical to end-product qualities. A central composite rotatable design (7) was used to incorporate these three independent variables in response surface modeling. The design required 20 experimental runs with 8 (2³) factorial points (3 levels for each variable), 6 star corner points (2 for each variable), and 6 center points, ultimately yielding 5 levels for each variable and permitting a better assessment of their quadratic effects.

**Physical Parameters**

Several physical parameters were selected from those that have been used to describe the physical properties of nonextruded rice grains.

**Thousand Kernel Weight.** The 1,000 kernel weight (measured in grams) of rice grains was determined using a digital electronic balance (Contech Instruments Ltd.) that is accurate to 0.01 g. To evaluate 1,000 kernel weight, 100 randomly selected grains from the bulk sample were averaged (21).

**Length/Breadth Ratio.** Rice grains were transferred to a medium grain rice tray, scanned at 300 dpi, and analyzed using a digital image analysis system (SeedCount, Weiss Enterprises and SeedCount Australasia) that measure the true grain length and breadth of the grain. The length/breadth ratio was calculated, and the shape of the extruded rice was determined per SES/INGER, IRRI, and systematic classification.

**Bulk Density.** Bulk density (measured in grams/liter) was determined by filling a cylindrical container (500 mL volume) with rice grains to a height of 150 mm at a constant rate and then weighing the contents (16). No separate manual compaction of the grains was done. Bulk density was calculated from the mass of the grains and the volume of the container.

**Breaking Strength.** Breaking strength (breaking force/unit of cross-section area) was measured using a single-cycle compression test in a texture analyzer (TA-XT2i, Stable Microsystems) with a 500 N load cell. A three point breaking test (22) was used to measure the maximum force required to break the refabricated rice samples. Eight measurements were made for each sample, and the average value was used.

### Table I. Analysis of variance and model statistics for physical properties of refabricated rice

<table>
<thead>
<tr>
<th>Term</th>
<th>Product Responsea</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TKW (g)</td>
</tr>
<tr>
<td>F value</td>
<td>53.46</td>
</tr>
<tr>
<td>P &gt; F</td>
<td>0.0001</td>
</tr>
<tr>
<td>Mean</td>
<td>19.47</td>
</tr>
<tr>
<td>SD</td>
<td>0.09</td>
</tr>
<tr>
<td>CV</td>
<td>0.46</td>
</tr>
<tr>
<td>R²</td>
<td>0.979</td>
</tr>
<tr>
<td>Adjusted R²</td>
<td>0.961</td>
</tr>
<tr>
<td>Predicted R²</td>
<td>0.874</td>
</tr>
<tr>
<td>Adequate precision</td>
<td>26.43</td>
</tr>
<tr>
<td>Lack of fit</td>
<td>0.100</td>
</tr>
</tbody>
</table>

a TKW = 1,000 kernel weight; L/B = length/breadth ratio; BD = bulk density; and BS = breaking strength.

### Table II. Effects of extrusion conditions on physical properties of refabricated rice

<table>
<thead>
<tr>
<th>Run</th>
<th>Extrusion Conditiona</th>
<th>TKW (g)</th>
<th>L/Bb</th>
<th>BD (g/L)</th>
<th>BS (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>34.00 (-1)</td>
<td>18.76 ± 0.27</td>
<td>3.7 ± 0.03</td>
<td>880.62 ± 0.85</td>
<td>95.12 ± 0.55</td>
</tr>
<tr>
<td>2</td>
<td>42.00 (+1)</td>
<td>19.08 ± 0.07</td>
<td>3.61 ± 0.04</td>
<td>888.56 ± 1.10</td>
<td>96.26 ± 0.47</td>
</tr>
<tr>
<td>3</td>
<td>34.00 (-1)</td>
<td>18.69 ± 0.27</td>
<td>3.71 ± 0.03</td>
<td>879.45 ± 0.98</td>
<td>95.34 ± 0.73</td>
</tr>
<tr>
<td>4</td>
<td>42.00 (+1)</td>
<td>18.92 ± 0.24</td>
<td>3.66 ± 0.02</td>
<td>882.52 ± 0.52</td>
<td>96.29 ± 0.45</td>
</tr>
<tr>
<td>5</td>
<td>34.00 (-1)</td>
<td>19.82 ± 0.09</td>
<td>3.91 ± 0.02</td>
<td>841.47 ± 0.91</td>
<td>98.84 ± 0.69</td>
</tr>
<tr>
<td>6</td>
<td>42.00 (+1)</td>
<td>20.12 ± 0.12</td>
<td>3.86 ± 0.03</td>
<td>849.81 ± 0.69</td>
<td>102.64 ± 0.88</td>
</tr>
<tr>
<td>7</td>
<td>34.00 (-1)</td>
<td>19.71 ± 0.09</td>
<td>3.94 ± 0.03</td>
<td>838.61 ± 1.15</td>
<td>98.34 ± 0.91</td>
</tr>
<tr>
<td>8</td>
<td>42.00 (+1)</td>
<td>19.94 ± 0.08</td>
<td>3.88 ± 0.04</td>
<td>846.53 ± 1.19</td>
<td>101.56 ± 1.02</td>
</tr>
<tr>
<td>9</td>
<td>31.00 (+1.682)</td>
<td>19.19 ± 0.12</td>
<td>3.84 ± 0.02</td>
<td>853.21 ± 1.32</td>
<td>95.72 ± 0.94</td>
</tr>
<tr>
<td>10</td>
<td>44.00 (+1.682)</td>
<td>19.79 ± 0.07</td>
<td>3.68 ± 0.03</td>
<td>881.2 ± 0.51</td>
<td>99.65 ± 0.55</td>
</tr>
<tr>
<td>11</td>
<td>58.00 (0)</td>
<td>19.70 ± 0.08</td>
<td>3.73 ± 0.04</td>
<td>877.12 ± 1.08</td>
<td>98.22 ± 1.08</td>
</tr>
<tr>
<td>12</td>
<td>38.00 (0)</td>
<td>19.53 ± 0.08</td>
<td>3.78 ± 0.03</td>
<td>861.74 ± 1.06</td>
<td>97.49 ± 0.99</td>
</tr>
<tr>
<td>13</td>
<td>38.00 (0)</td>
<td>18.62 ± 0.05</td>
<td>3.59 ± 0.04</td>
<td>898.3 ± 0.84</td>
<td>94.88 ± 0.87</td>
</tr>
<tr>
<td>14</td>
<td>38.00 (0)</td>
<td>20.22 ± 0.07</td>
<td>3.97 ± 0.02</td>
<td>836.45 ± 0.96</td>
<td>102.73 ± 1.01</td>
</tr>
<tr>
<td>15</td>
<td>38.00 (0)</td>
<td>19.57 ± 0.06</td>
<td>3.82 ± 0.03</td>
<td>864.52 ± 0.89</td>
<td>97.4 ± 0.71</td>
</tr>
<tr>
<td>16</td>
<td>38.00 (0)</td>
<td>19.6 ± 0.05</td>
<td>3.8 ± 0.02</td>
<td>872.46 ± 0.99</td>
<td>97.48 ± 0.44</td>
</tr>
<tr>
<td>17</td>
<td>38.00 (0)</td>
<td>19.54 ± 0.06</td>
<td>3.84 ± 0.02</td>
<td>863.79 ± 1.09</td>
<td>97.38 ± 0.98</td>
</tr>
<tr>
<td>18</td>
<td>38.00 (0)</td>
<td>19.62 ± 0.07</td>
<td>3.79 ± 0.04</td>
<td>874.32 ± 0.94</td>
<td>97.5 ± 1.13</td>
</tr>
<tr>
<td>19</td>
<td>38.00 (0)</td>
<td>19.58 ± 0.03</td>
<td>3.81 ± 0.03</td>
<td>870.96 ± 0.91</td>
<td>97.45 ± 1.33</td>
</tr>
<tr>
<td>20</td>
<td>38.00 (0)</td>
<td>19.45 ± 0.05</td>
<td>3.83 ± 0.05</td>
<td>855.52 ± 2.05</td>
<td>97.52 ± 0.54</td>
</tr>
</tbody>
</table>

a Actual and coded values. Coded values are given in parentheses. MC = moisture content.

b TKW = 1,000 kernel weight; L/B = length/breadth ratio; BD = bulk density; and BS = breaking strength.

c Sample grain shape was long and slender per systematic classification of rice.
Statistical Analysis
Responses obtained as a result of the proposed experimental design were subjected to regression analysis to assess the effects of moisture content, screw speed, and temperature. Second-order polynomial regression models were established for the dependent variables to fit experimental data for each response using statistical software (Design-Expert 8, Stat-Ease, Inc.):

\[ y_i = b_0 + \sum_{i=1}^{3} b_i x_i + \sum_{i=1}^{3} b_{ii} x_i^2 + \sum_{i=1}^{3} \sum_{j=i+1}^{3} b_{ij} x_i x_j \]

where \( x_i \) (i = 1, 2, or 3) are independent variables (moisture content, screw speed, or temperature, respectively) and \( b_0, b_i, b_{ii}, \ldots b_{ij} \) are coefficients for intercept, linear, quadratic, and interactive effects, respectively. Data were analyzed using multiple regression analysis, and statistical significance of the terms was examined using analysis of variance (ANOVA) for each response. The adequacy of the regression model was checked using correlation coefficients. The lack-of-fit test was used to judge the adequacy of the model fit. To aid in visualization of variation in responses with respect to processing variables, a series of three-dimensional response surfaces plots were drawn.

Optimization
Optimization is used to maximize a desired quality or minimize an undesired one. Processing variables with desired optimal values correspond to optimal extrusion conditions. Thousand kernel weight, length/breadth ratio, bulk density, and breaking strength are the major parameters that determine the physical properties of refabricated rice. Therefore, optimal conditions were determined for production of refabricated rice from variety PR-116 based on these parameters. The targeted optimal values for 1,000 kernel weight, length/breadth ratio, bulk density, and breaking strength were 19.5 g, 3.77, 840 g/L, and 94.76 N, respectively. The response surface of desirability function was used for numerical optimization.

RESULTS AND DISCUSSION
Physical Parameters
The regression models for 1,000 kernel weight, length/breadth, bulk density, and breaking strength were highly significant (\( P < 0.01 \)), with high correlation coefficients \( R^2 = 0.98, 0.98, 0.92, \text{ and } 0.99 \), respectively. None of the models showed significant lack of fit, indicating that all the second-order polynomial models correlated well with the measured data. The predicted \( R^2 \) was in reasonable agreement with the adjusted \( R^2 \) for all parameters. The adequate precision values were >4, indicating adequate model discrimination (Table I).

Thousand Kernel Weight and Breaking Strength. The mean values for 1,000 kernel weight and breaking strength of refabricated rice obtained under different extrusion conditions are listed in Table II. ANOVA (Table I) showed that both 1,000 kernel weight and breaking strength were significantly affected by screw speed (\( S \)), barrel temperature (\( T \)), and moisture content (\( M \)). The fitted regression equations for 1,000 kernel weight and breaking strength are shown in Equations 1 and 2, respectively:

\[
1,000 \text{ kernel weight} = 19.65 + 0.153M - 0.059S + 0.507T \\
\text{Breaking strength} = 97.46 + 1.15M - 0.187S + 2.317T + 0.454T^2
\]

Response surface plots of 1,000 kernel weight and breaking strength versus two independent variables at a time are shown in Figures 1 and 2, respectively. The positive coefficients for the linear terms of moisture content and temperature indicate that both 1,000 kernel weight and breaking strength increased with increases in these variables. This was possibly due to increased tensile strength of grains caused by gelatinization of starch granules. Starch under high moisture and temperature conditions becomes gelatinized and then retrogrades after cooling. Through gelatinization, \( \alpha \)-amylose molecules leach out of the starch granule network and diffuse into the surrounding aqueous medium outside the granules, which when fully hydrated is at maximum viscosity. Cooling brings about retrogradation, whereby amylose molecules reassociate with each other and form a tightly packed structure. This increases the formation of type 3 resistant starch, which makes the refabricated grains harder and glassier and, thereby, increases the 1,000 kernel weight. Similar results have also been reported in studies by Thakur and Gupta (19) and Khatoon and Prakash (13) for raw and parboiled rice.

The negative coefficients for the linear term of screw speed indicate that 1,000 kernel weight and breaking strength decreased with an increase in screw speed, which reduced the residence time of the material in the barrel (8). This reduced the energy received by the material and resulted in partial gelatinization.
of the starch, which could possibly have lowered the breaking strength and 1,000 kernel weight of the refabricated rice grains. Sun and Muthukumarappan (17) reported similar results when screw speed increased from 180 to 220 rpm.

**Bulk Density.** The fitted regression model for bulk density (Eq. 3) demonstrates that bulk density was significantly affected by moisture content and barrel temperature:

\[
\text{Bulk density} = 865.84 + 5.429M - 2.857S - 18.93T
\]  
(3)

The positive coefficient of the linear term of moisture content indicates that bulk density increased with an increase in moisture. Response surface plots of bulk density versus two independent variables at a time are shown in Figure 3. The high dependence of bulk density on feed moisture content reflects its influence on the elasticity of starch-based materials. Increased feed moisture during extrusion may reduce the elasticity of the dough through plasticization of the melt. This results in reduced specific mechanical energy, which decreases the expansion and increases the bulk density of grains. Sun and Muthukumarappan (17) found that with increasing feed moisture, bulk density increased steadily. Hagenimana et al. (9) reported that bulk density increased with an increase in feed moisture at low barrel temperature, whereas the opposite effect occurred at high barrel temperature.

The negative coefficients of the linear terms of temperature and screw speed (Eq. 3) indicate that bulk density decreased with increases in barrel temperature and screw speed, probably due to higher starch gelatinization. According to Case et al. (4), as gelatinization increases, the volume of extrudates increases and bulk density decreases. Higher temperatures lower the viscosity of the dough mass in the extruder, resulting in higher linear velocity at the die, which reduces the bulk density of the extrudates. Increasing screw speed tends to increase the shearing effect, which causes protein and starch molecules to be stretched farther apart, weakening bonds and resulting in a puffier product with lower bulk density. Similar results were reported by Chávez-Jáuregui et al. (5) and Meng et al. (14) for various starch-based extruded products. Sun and Muthukumarappan (17) reported that bulk density increased with increasing screw speed, but provided no explanation.

**Length/Breadth Ratio.** Both bulk density and length/breadth ratio represent the extent of extrudate expansion. Therefore, it might be expected that these two properties would be negatively correlated, with higher length/breadth ratio contributing to lower bulk density, but Park et al. (15) reported that this is not always the case. In the current study, a significant inverse relationship was found between length/breadth ratio and bulk density (Table II).

Response surface plots of length/breadth versus two independent variables at a time are shown in Figure 4. The fitted regression model for length/breadth ratio (Eq. 4) shows that length/breadth ratio was significantly affected by moisture, barrel temperature, and screw speed:

\[
\text{Length/breadth} = 3.81 - 0.038M + 0.014S + 0.113T
\]  
(4)

Unlike bulk density, length/breadth ratio decreased with an increase in moisture content and increased with increases in barrel temperature and screw speed. Low moisture and high screw speed and barrel temperature led to a decrease in bulk density, which might have been due to expansion of the refabricated rice grains, which could possibly have lowered the breaking strength and 1,000 kernel weight of the refabricated rice grains. Sun and Muthukumarappan (17) reported similar results when screw speed increased from 180 to 220 rpm.
cated rice grains, as indicated by the increase in length/breadth ratio. The data presented in Table II indicate that refabricated grains with smaller length/breadth ratios had higher bulk densities. This was similar to the results reported by Vanaja and Babu (20) for parboiled and nonparboiled brown rice.

Optimization
Using the desirability function method, optimal extrusion conditions were obtained. The desirability value obtained was 0.802 (Fig. 5). A moisture content of 36%, screw speed of 130 rpm, and temperature of 89.5°C were predicted by response surface methodology to be the optimal conditions for producing refabricated rice with a closer resemblance to nonextruded rice grain (Fig. 6). The predicted response values and actual response values were fairly similar. The variation in actual response values was within 3% of the predicted values (Table III).

CONCLUSIONS
Response surface modeling revealed the significant effects of three important extrusion parameters (screw speed, feed mois-
ture content, and barrel temperature) on the physical properties of twin-screw extruded, refabricated rice grains. Within the range of this experiment, barrel temperature had the greatest impact on the physical properties of refabricated rice. The effects of barrel temperature on most of the properties of refabricated rice were linear; however, the effect was quadratic for breaking strength.

Extrusion processing can be ideal for production of refabricated rice, but because it is a complex multivariate process, careful control of extrusion parameters is required to maintain product quality. As a result, if commercial utilization of refabricated rice fortified with micronutrients is desired, further research on process optimization is needed to produce grains with improved quality and better consumer acceptability.

Acknowledgments
We thank Amarjeet Kaur (senior milling technologist, Department of Food Science and Technology) for providing the necessary facilities for the smooth conduct of this investigation.

References

Table III. Predicted versus actual responses

<table>
<thead>
<tr>
<th>Term</th>
<th>TKW (g)</th>
<th>L/B</th>
<th>BD (g/L)</th>
<th>BS (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted</td>
<td>19.20</td>
<td>3.85</td>
<td>852.26</td>
<td>95.76</td>
</tr>
<tr>
<td>Actual</td>
<td>19.31</td>
<td>3.78</td>
<td>863.54</td>
<td>98.12</td>
</tr>
<tr>
<td>Variation</td>
<td>0.57</td>
<td>1.82</td>
<td>1.32</td>
<td>2.46</td>
</tr>
</tbody>
</table>

* TKW = 1,000 kernel weight; L/B = length/breadth ratio; BD = bulk density; and BS = breaking strength.