Physical and Nutritional Properties of Corn Masa By-product Streams

Kurt A. Rosentrater  
_Iowa State University, karosent@iastate.edu_

Rolando A. Flores  
_United States Department of Agriculture_

Thomas L. Richard  
_Iowa State University_

Carl J. Bern  
_Iowa State University, cjbern@iastate.edu_

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Abstract
Production of corn masa-based products is flourishing in the United States, as is the generation of masa processing waste. Masa by-products have potential for value-added utilization, an option which could produce less pollution in the environment and economic benefits for masa processors. Physical and nutritional properties of these byproducts are needed for the proper design of processing operations and by-product applications, but information concerning masa byproducts is not currently available. Thus the objective of this study was to fully characterize typical masa by-product streams. The masa by-products studied had moisture contents between 88.15% and 89.29% (w.b.), water activity values between 0.999 and 1.000, densities between 1030.85 and 1047.32 kg/m³, yield stress values between 1440.04 and 1618.08 N/m², pH values between 6.17 and 6.30, Hunter L values between 35.15 and 49.13, a values between 0.27 and 0.98, and b values between 6.85 and 9.38. Drying curves were developed to predict drying behavior. The dried by-products had protein contents between 4.76% and 4.90% (d.b.), crude fat contents from 0.74% to 5.76% (d.b.), ash contents between 17.41% and 19.09% (d.b.), and carbohydrate contents from 71.93% to 75.41% (d.b.), which was due primarily to fiber, with hemicellulose levels of 20.82% to 24.06% (d.b.) and cellulose between 30.55% and 31.83% (d.b.). Dry masa by-products also consisted of 4.68% (d.b.) calcium. Therefore, dehydrated masa by-products seem very suitable for use as livestock feed additives.

Keywords
Evaluation, Food processing, Food waste, Residue characterization, Residue utilization

Disciplines
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PHYSICAL AND NUTRITIONAL PROPERTIES
OF CORN MASA BY-PRODUCT STREAMS

K. A. Rosentrater, R. A. Flores, T. L. Richard, C. J. Bern

ABSTRACT. Production of corn masa-based products is flourishing in the United States, as is the generation of masa processing waste. Masa by-products have potential for value-added utilization, an option which could produce less pollution in the environment and economic benefits for masa processors. Physical and nutritional properties of these by-products are needed for the proper design of processing operations and by-product applications, but information concerning masa byproducts is not currently available. Thus the objective of this study was to fully characterize typical masa by-product streams. The masa by-products studied had moisture contents between 88.15% and 89.29% (w.b.), water activity values between 0.999 and 1.000, densities between 1030.85 and 1047.32 kg/m³, yield stress values between 1440.04 and 1618.08 N/m², pH values between 6.17 and 6.30, Hunter L values between 35.15 and 49.13, a values between 0.27 and 0.98, and b values between 6.85 and 9.38. Drying curves were developed to predict drying behavior. The dried by-products had protein contents between 4.76% and 4.90% (d.b.), crude fat contents from 0.74% to 5.76% (d.b.), ash contents between 17.41% and 19.09% (d.b.), and carbohydrate contents from 71.93% to 75.41% (d.b.), which was due primarily to fiber, with hemicellulose levels of 20.82% to 24.06% (d.b.) and cellulose between 30.55% and 31.83% (d.b.). Dry masa by-products also consisted of 4.68% (d.b.) calcium. Therefore, dehydrated masa by-products seem very suitable for use as livestock feed additives.

Keywords. Evaluation, Food processing, Food waste, Residue characterization, Residue utilization.

Agricultural processing industries produce great quantities of waste materials. From 1991 to 1992 agribusinesses in Kansas alone produced over 72 000 Mg/yr of waste products and processing residues. Approximately 10% (7173 M g/yr) of these wastes were attributable to the grain processing industry (Nelson and Flores, 1994). Due to heightened economic and environmental concerns, landfilling has declined as the waste disposal method of choice, and disposal alternatives have been more frequently investigated. Current options include reprocessing/recycling, resale, incineration, composting, biomass energy production, land application as soil conditioning ingredients, and reuse as livestock feed ingredients. The last alternative includes both direct feeding of the waste products and feeding the by-products after further processing (i.e., dehydration, extrusion, or blending with other feed components) (Bohlsen et al., 1997).

In recent years, many research efforts have been aimed at the development of livestock feed additives from agricultural wastes and by-products. One aspect has included the investigation of residential wastes as potential feed products (Polanski, 1992). Another area has included the development of feed ingredients from slaughterhouse by-products (Luzier and Summerfelt, 1995; Martins and Guzman, 1994; Wang et al., 1997). The utilization of grain by-products as livestock feed components has also been extensively researched (Ham et al., 1994, 1995; Hussein and Berger, 1995; Larson et al., 1993). Corn masa production is one facet of the grain processing industry that generates large quantities of waste materials, but to date, has received little research attention regarding alternatives for by-product disposal.

Corn masa is used in the production of corn snack foods and tortilla chips, and has traditionally been utilized in the preparation of tortillas, which have been a staple in the diet of Mexican and Central American peoples for centuries. Foods made with corn masa include tacos, tostadas, tamales, quesadillas, panuchos, enchiladas, and others (Krause et al., 1992; Ortiz, 1985; Serna-Saldivar et al., 1990). Currently, Mexican foods and corn-based snacks in the United States are becoming more popular. Over $4 billion worth of Mexican foods were marketed in 1986, and approximately $2.5 billion worth of tortilla chips were produced in 1994 (Gomez et al., 1987; Wood, 1994). Corn masa is produced by simulating ancient Aztec methods on an industrial-scale. Whole corn is boiled with 120 to 300% water (original corn weight basis) and 0.1 to 2.0% lime (original corn weight basis) for 0.5 to 3.0 h at 80 to 100°C,
and is then steeped for up to 24 h. This process, called nixtamalization, can be either a batch process or a continuous process, depending on production equipment. The cooked grain (nixtamal) is then separated from the steep liquor (nejayote), which is rich in lime and dissolved corn pericarp tissue, is washed to remove any excess lime and pericarp, and is then stone ground to produce corn masa. The masa will then be molded, cut, or extruded and then baked or fried to make tortillas, corn chips, or tortilla chips; or it will be dried and milled into flour (Gomez et al., 1987; Rooney and Serna-Saldivar, 1987; Serna-Saldivar et al., 1990).

The steep liquor and the rinse water contain between 2 and 6% total (dissolved and suspended) solids. Generally the suspended solids (50 to 60% of the total solids) are removed by screening, centrifugation, or decanting, and disposed of in landfills. The remaining water and dissolved solids are sent to municipal facilities for treatment. The total solids in the waste stream, which consist primarily of fiber-rich pericarp tissues, represent corn dry matter loss that occurs during processing. Estimates of the original corn dry matter loss have ranged from 5.0% to 17.0%. The following were found in the literature: 8.5 to 12.5% (Pflugfelder et al., 1988), 8.0 to 17.0% (Rooney and Serna-Saldivar, 1987), 7.0 to 13.0% (Khan et al., 1982), 5.0 to 14.0% (Katz et al., 1974), 11.0 to 12.0% (Bressani et al., 1958), and 13.3% (Gonzalez de Palacios, 1980). Corn dry matter loss during nixtamalization is affected by many processing variables, including corn hybrid and quality, lime type and concentration, cooking and steeping times and temperatures, friction during washing and transport, and process equipment used. These processing losses can be economically significant due to lost masa yield, waste processing and disposal costs, and potential environmental pollution. This waste generation is of particular concern in areas of substantial masa processing, such as Mexico City, where over 2400 Mg of corn is processed every day into corn masa for tortilla production (Gonzalez-Martinez, 1984).

Gonzalez-Martinez (1984) investigated four biological treatment options for “nejayote”, including activated sludge, anaerobic contact processing, a submerged aerobic fixed-film cascade reactor, and an anaerobic packed-bed reactor. However, little research has been conducted into alternative disposal methods for corn masa dry matter losses (i.e., the separated suspended solids), and none could be found regarding the utilization of corn masa waste solids in livestock feed rations. To effectively utilize and add value to these by-products, physical and nutritional properties for corn masa residual streams must be quantified. Characterization of by-product materials provides data that are essential for livestock diet formulation, design of equipment and processing facilities, and optimization of unit operations such as spray drying, extrusion, blending, mixing, separating, heating, freezing, dehydration, and material flow (Ferris et al., 1995; Stroshine and Hamann, 1995). Little information has been gathered concerning the properties of corn masa by-products, however. Because the demand for corn masa-based products is increasing in the United States, the objective of this study was to characterize and quantify the physical and nutritional properties of typical corn masa by-product streams so that subsequent by-product applications may effectively be developed for these waste materials. Physical properties studied included moisture content, water activity, density, yield stress, pH, color, and drying analysis. Nutritional properties studied included protein, crude fat, ash, mineral composition, amino acid composition, and fiber content.

**MATERIALS AND METHODS**

**SAMPLE COLLECTION AND PREPARATION**

Corn masa by-product samples, which were gray, pasty, semi-solid slurries, were obtained from a local white corn masa processing facility after the decanting process (i.e., the samples collected were the separated suspended solids from the waste stream). Five 3.5 L samples were collected at random times from random batches and random production runs, from both batch and continuous processing lines during the fall of 1996. The 10 samples were then placed in frozen storage at −10°C until testing commenced. Prior to analysis, the samples were thawed at room temperature (25°C ± 2°C) for 24 h. All physical properties, except moisture content and drying analysis, were determined at room temperature. All nutritional tests were conducted as specified by the standard method used for each property.

**EXPERIMENTAL DESIGN**

To investigate the properties of typical corn masa by-products, five samples from each of two processes (a batch process and a continuous process) were analyzed; thus two populations were present in this study. All properties were studied using a completely randomized design. For all physical property testing (moisture content, water activity, density, yield stress, pH, color, and drying analysis), five replicates were taken from each sample, which led to an overall sample size of 25 experimental units for each production process (population). This maintained the Type-I (α) and Type-II (β) error rates at the 0.05 level and allowed the detectable statistically significant difference between populations to remain at 1.0 standard deviations. Protein, crude fat, and ash testing were performed with two replicates taken from each sample, which led to an overall sample size of 10 experimental units from each population. This maintained the Type-I (α) and Type-II (β) error rates at the 0.05 level, but the detectable difference between populations increased to 1.8 standard deviations. Fiber analysis was conducted with three replicates from each sample, which produced a sample size of 15 experimental units for each production process. This maintained the Type-I (α) and Type-II (β) error rates at the 0.05 level, and the detectable difference between populations was set at 1.4 standard deviations (Nelson, 1985). Formal statistical analyses on the collected data were performed via Microsoft Excel (Microsoft, 1993) and SAS (SAS, 1992) software.

Amino acid composition was studied on the continuous-process samples only, as was mineral analysis. One replicate from each of the five samples was used in the amino acid study; whereas, one replicate from two of the five samples was randomly selected for mineral analysis. Neither amino acid composition nor mineral composition was included in the formal statistical analysis that was conducted on all other physical and nutritional properties.
PHYSICAL PROPERTIES

Moisture Content and Water Activity. Moisture content (wet basis, w.b.) of the masa by-product samples was determined using a method similar to AACC Method 44-15A (“Moisture-Air-Oven Methods”) (AACC, 1995). By-product samples of 2 to 3 g were placed in open tared, aluminum moisture dishes and dried at 130°C for 3 h in a forced-convection laboratory oven (Thelco Model 160DM, Precision Scientific, Inc., Chicago, Ill.). After drying, the samples were allowed to cool in a desiccator, and sample mass was then measured with an electronic balance (Model A–250, Denver Instrument Co., Arvada, Colo.). To determine water activity of the masa by-products, 4-g samples were placed in a previously calibrated water activity meter (Aqualab Model CX-2, Decagon Devices, Inc., Pullman, Wash.).

Mass Density. The density of each by-product sample was determined using a specific gravity cup (Model H-38000-12, Cole-Parmer Instrument Co., Barrington, Ill.) and an electronic balance. The specific gravity cup has a known mass and volume; hence, to measure sample density, the cup was filled completely with sample material, the lid was placed on the cup, excess sample material was removed, and the filled cup was then weighed on the balance.

Yield Stress. The yield stress of the by-product samples was determined using the vane method with a digital viscometer (Model HBVD II+, Brookfield Engineering, Stoughton, Mass.) and a four-finned vane, which was 1.01 cm in height and 5.3 cm in diameter; each fin was 1.4 mm in width. By-product samples were placed in a 150-mL beaker which was 8 cm in height and 5.3 cm in diameter; the vane was then placed 2 cm below the sample surface, and a controlled constant shear rate of 0.34 s⁻¹ (0.5 rpm) was applied. Using the vane method with a controlled shear rate, the yield stress was determined using the following equation:

\[ T_m = \frac{\pi D^3}{2} \left( \frac{H}{D} + \frac{1}{3} \right) \tau_y \]  

where \( T_m \) is the torque exerted on the vane at yielding, \( D \) is the overall vane diameter, \( H \) is the overall vane height, and \( \tau_y \) is the resultant yield stress (Dzuy and Boger, 1985; Yoo et al., 1995).

pH. To determine the pH of the masa by-product samples, 10-g samples were placed in a 50-mL glass beaker. A bench-top pH meter (Model PHB-62, Omega Engineering, Inc., Stamford, Conn.) was then used to measure the pH.

Color. The color of each masa by-product sample was determined using a Hunter Colorimeter (Model LabScan SN-12414, Hunter Associates Laboratory, Inc., Reston, Va.), using a view-port and view-area size of 1.27 cm (0.5 in.), and the \( L-a-b \) opposable color scales (Hunter, 1983). The samples were placed in 100 mm × 15 mm plastic petri dishes and were positioned in the instrument for color determination after proper instrument calibration.

Drying Analysis. The drying studies that were performed on the masa by-products were similar to those conducted by Rosentrater and Flores (1997) on swine blood components. Masa by-product samples of 2 to 3 g were placed in aluminum moisture dishes that were 8 cm in diameter and 2.5 cm in height and were placed in a forced-convection laboratory oven (Thelco Model 160DM, Precision Scientific, Inc., Chicago, Ill.). Samples were dried at temperatures of 80, 100, and 120°C for 2 h, and sample mass over time was measured with an electronic balance. Sample masses were recorded every 5 min during the first hour of testing and every 10 min thereafter. Thus, drying curves were developed on a dry basis (d.b.) and drying rate prediction equations as a function of moisture content and drying temperature were developed for the two by-products.

NUTRITIONAL PROPERTIES

Proximate Composition. Proximate analyses of dry masa by-product samples included the determination of protein, crude fat, and ash contents. Protein and crude fat analyses were conducted by the Meat Laboratory at Iowa State University, Ames, Iowa. Protein analysis followed the AACC Standard Method 46-11A (“Crude protein-improved Kjeldahl method, copper catalyst modification”), using a factor of N × 6.25. Crude fat was determined using Method 30-25 (“Crude fat in wheat, corn, and soy flour, feeds, and cooked feeds”) (AACC, 1995). Ash content was determined using the AACC Standard Method 08-03 (“Ash-rapid (2-hour, 600°F) method”, 1995), which utilized 2 g samples placed in a muffle furnace at 600°F for 2 h. Because protein, fat, ash, and carbohydrate contents sum to 100% in the dry by-product, the carbohydrate contents of the dry masa by-product samples could be calculated by difference.

Fiber Composition. Fiber analysis was conducted by the Forage Quality Laboratory at Iowa State University, Ames, Iowa, using the Van Soest detergent system to determine Neutral Detergent Fiber (NDF), Acid Detergent Fiber (ADF), and lignin fractions of the masa by-product samples. These methods are widely used for the determination of fiber composition of biological materials and potential livestock feed ingredients (Moore and Hatfield, 1994; Van Soest et al., 1991).

Mineral Composition. Mineral analyses of the masa by-product samples were conducted by the Analytical Services Laboratory at Iowa State University, Ames, Iowa, and included the determination of calcium, potassium, magnesium, and phosphorous. Prior to analysis, all samples were dried at 103°C for 24 h, and the portions used for calcium, potassium, and magnesium were then digested in nitric acid and hydrogen peroxide. Calcium and magnesium determinations were performed using Method SMEWW 3111 B, which utilized flame atomic absorption spectrophotometry, and potassium analysis was conducted using Method SMEWW 3500-K D, which utilized flame photometry (APHA, 1995). Phosphorous content was determined by dry ashing the samples using Method AOAC 2.020c and then performing spectrophotometric measurements using the molybdovanadophosphate method prescribed in Method AOAC 2.026 (AOAC, 1980).

Amino Acid Composition. Amino acid profiles of the masa by-product samples were conducted by the Protein Structure Core Facility at the University of Nebraska Medical Center, Omaha, Nebr. The samples were dried, subjected to 6 N HCl hydrolysis for 20 h at 110°C, and
RESULTS AND DISCUSSION

PHYSICAL PROPERTIES

Moisture Content and Water Activity. The moisture content results are shown in Table 1. Masa by-products are very wet materials, even after the decanting process, and have moisture contents near 90% (w.b.). These moisture levels preclude the direct shipping of the by-product materials for incorporation into disposal alternatives; instead, a drying mechanism will be required to reduce the high cost which is associated with the transportation of water. Additionally, the water activity levels for the masa by-product samples (Table 1) are greater than 0.999; thus the by-products are susceptible to microbial spoilage.

Water activity quantifies the amount of "free" water (i.e., unbound water) available in materials for use by microorganisms and chemical agents, and hence is a measure of susceptibility to spoilage and deterioration. Products with no free water (aW = 0) are not at risk for spoilage; whereas, materials with 100% free water (aW = 1.0) are at risk for rapid spoilage, which is the case for masa by-products. Materials become safe from yeast growth below approximately 0.9, safe from bacteria growth below approximately 0.8, and safe from mold growth below approximately 0.6 (Barbosa-Canovas and Vega-Mercado, 1996).

In order to effectively utilize masa by-products, dehydration is necessary to prevent microbial spoilage, and can be accomplished through drying, blending, or extrusion processing to an acceptable moisture level of approximately 12% (w.b.), which is typically recommended for feed products because it substantially reduces transportation costs and is microbiologically safe (Beauchat, 1981; Wang et al., 1997).

Mass Density. As shown in Table 1, masa by-products had density values slightly greater than that of water (approx. 999 kg/m3). This was not unexpected due to the high moisture contents of the by-product samples. The mean values were significantly different (p < 0.05), however, which may reflect differences in the resulting material structures due to differences in the batch and continuous processing operations.

Yield Stress. Masa by-products, as shown in Table 1, have very large yield stresses that are similar in magnitude to those of minced fish paste (1600-2300 N/m2) (Nakayama et al., 1980). Yield stress is a rheological parameter that quantifies the shear stress required to initiate flow in a liquid or semi-solid material, results from the existence of particle structures, and is vital for the design of transport processes and operations (Steffe, 1992). Because masa by-products have such large yield stress values, special considerations will need to be given to conveying operations for these materials during further processing.

pH. The pH results are shown in Table 1. It was expected that pH values would be fairly high for the masa by-product samples because nixtamalization generally employs a pH greater than 10.0 during the lime cooking process (Serna-Saldivar et al., 1990). Instead, the resulting pH values were fairly low (between 6.17 and 6.30). This may have occurred due to a large proportion of the lime washing away with the rinse water during processing, or possibly due to microbial activity during transit between the processing facility and the laboratory. Investigating the cause of the low pH values would be a valuable future study.

Color. The Hunter L, a, and b results are shown in Table 1, and show some differences in color between the batch-processed and the continuous-processed masa by-products, even though both processes used the same source and hybrid of raw white corn. Essentially, these results describe masa by-products as gray material with a small degree of yellowness.

Drying Analysis. Drying analysis of biological materials is important for the proper design of drying processes and equipment. For the masa by-products in this study, sample mass over time was monitored and used to determine moisture contents and resulting drying rates at drying temperatures of 80, 100, and 120°C. A multiple regression procedure with STEPWISE model selection (SAS, 1992), selecting only significant terms, was then used to determine polynomial regression prediction equations for drying rates as a function of moisture content and drying temperature. The regression equation for the drying of batch-processed masa by-products, which had a coefficient of determination (R2) of 0.93 and a sample variance of 0.099, was determined to be:

\[
DR = (0.0058) - (0.5719)M + (0.7625)M^2
- (0.5061)M^3 + (0.1191)M^4 - (0.0117)M^5
+ (0.0004)M^6 + (0.0111)(M)(T)
\]

(2)

where DR is the predicted by-product drying rate (g H2O/g sample-h), M is the material moisture content (decimal dry basis, d.b.), and T is the oven drying temperature (°C). The graph of this regression function is shown in Figure 1. A similar regression equation for the drying of continuous-processed masa by-products, which had a coefficient of determination (R2) of 0.90 and a sample variance of 0.060, was determined to be:

\[
DR = (0.0005) - (0.5719)M + (0.7625)M^2
- (0.5061)M^3 + (0.1191)M^4 - (0.0117)M^5
+ (0.0004)M^6 + (0.0111)(M)(T)
\]

(2)

Table 1. Physical and nutritional properties of corn masa by-products

<table>
<thead>
<tr>
<th>Property</th>
<th>Batch Process</th>
<th>Continuous Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Size (n)</td>
<td>Mean (%)</td>
<td>C.V. (%)</td>
</tr>
<tr>
<td>Moisture content (% w.b.)</td>
<td>25</td>
<td>89.29</td>
</tr>
<tr>
<td>Water activity (-)*</td>
<td>25</td>
<td>1.000</td>
</tr>
<tr>
<td>Density (kg/m3)*</td>
<td>25</td>
<td>1030.85</td>
</tr>
<tr>
<td>Yield stress (N/m²)*</td>
<td>25</td>
<td>1618.08</td>
</tr>
<tr>
<td>pH (-)</td>
<td>25</td>
<td>6.30</td>
</tr>
<tr>
<td>Color: Hunter L value (-)*</td>
<td>25</td>
<td>49.13</td>
</tr>
<tr>
<td>Color: Hunter a value (-)*</td>
<td>25</td>
<td>0.27</td>
</tr>
<tr>
<td>Color: Hunter b value (-)*</td>
<td>25</td>
<td>9.38</td>
</tr>
<tr>
<td>Protein (% d.b.)</td>
<td>10</td>
<td>4.76</td>
</tr>
<tr>
<td>Fat (% d.b.)*</td>
<td>10</td>
<td>0.74</td>
</tr>
<tr>
<td>Ash (% d.b.)</td>
<td>10</td>
<td>19.09</td>
</tr>
<tr>
<td>Carbohydrates (% d.b.)*</td>
<td>10</td>
<td>75.41</td>
</tr>
<tr>
<td>NDF (%)</td>
<td>15</td>
<td>54.97</td>
</tr>
<tr>
<td>ADF (%)</td>
<td>15</td>
<td>30.91</td>
</tr>
<tr>
<td>Calcium (% d.b.)*</td>
<td>15</td>
<td>0.36</td>
</tr>
<tr>
<td>Potassium (% d.b.)*</td>
<td>2</td>
<td>---</td>
</tr>
<tr>
<td>Magnesium (% d.b.)*</td>
<td>2</td>
<td>---</td>
</tr>
<tr>
<td>Phosphorus (% d.b.)*</td>
<td>2</td>
<td>---</td>
</tr>
</tbody>
</table>

* Denotes a significant difference between batch and continuous-process means at the 0.05 level.
The graph of this prediction equation is shown in figure 2.

When a material is dried, water is first removed within a "constant drying rate" period, during which both surface and unbound water evaporate at a constant rate. After the unbound water has been removed, the drying rate begins to fall, and the process enters a "falling rate" period, of which there may be more than one. At this point, drying is no longer governed by surface evaporation but by mass transfer within the material. This moisture transfer may occur due to several processes, including evaporation within the solid material, diffusion, and capillary movement, and may be adversely affected by gravity, material pore structures, and case hardening at the material surface (Barbosa-Canovas and Vega-Mercado, 1996).

Second derivative analysis was used to determine the inflection points in the regression curves, and thus determine where the critical moisture contents occurred (i.e., where the falling rate periods began). Batch-processed masa by-products at 80°C had falling rate periods that began at moisture contents of 6.08, 3.25, and 0.82 (d.b.); at 100°C had falling rate periods that began at moisture contents of 5.97, 3.27, and 0.82 (d.b.); and at 120°C had falling rate periods that began at 5.95, 3.28, and 0.82 (d.b.). Continuous-processed masa by-products at 80°C had falling rate periods that began at moisture contents of 7.81, 5.27, 2.61, and 2.00 (d.b.); at 100°C had falling rate periods that began at moisture contents of 7.80 and 4.41 (d.b.); and at 120°C had falling rate periods that began at moisture contents of 7.79 and 4.17 (d.b.). For continuous-processed by-products, critical moisture contents decreased with increasing drying temperature, but drying temperature seemed to have little effect on critical moisture content for batch-processed samples. Also, it appears that, at least initially, drying rates for the batch-processed by-product are higher than those for the continuous-processed by-product. The differences in drying behavior between the two processing techniques may be due to differences in the material structures which result from the cooking process used (i.e., continuous vs batch processing).

**Thermal Properties.** Although thermal analyses were not actually conducted, enough information was collected to estimate thermal conductivity, specific heat, and thermal diffusivity. Thermal conductivity can be estimated using two prediction equations (Anderson, 1950; Spells 1961):

\[
k = k_W X_W + k_S (1 - X_W)
\]

\[
k = 0.056 + 0.57X_W
\]

where \(k\) is the estimated thermal conductivity (W/m·K), \(k_W\) is the thermal conductivity of water (0.602 W/m·K), \(X_W\) is the mass fraction of water (-), and \(k_S\) is the thermal conductivity of organic solids (approx. 0.259 W/m·K). Using equation 4, predicted thermal conductivities of batch- and continuous-processed masa by-products were, respectively, 0.565 and 0.561 W/m·K, and with equation 5, 0.565 and 0.558 W/m·K. Specific heat can also be predicted using two equations (Stroshine and Hamann, 1995; Choi and Okos, 1986):
\[ c_p = 0.837 + 3.348M \]  
\[ c_p = 4.180X_W + 1.711X_p + 1.928X_f \]
\[ + 1.547X_c + 0.908X_a \]

where \( c_p \) is the estimated specific heat (kJ/kg·K), \( M \) is the moisture content (decimal wet basis — w.b.), \( X_p \) is the mass fraction of protein (-), \( X_f \) is the mass fraction of fat (-), \( X_c \) is the mass fraction of carbohydrates (-), and \( X_a \) is the mass fraction of ash (-). Using equation 6, the predicted values of specific heat for the batch- and continuous-processed masa by-products were, respectively, 3.826 and 3.788 kJ/kg·K, and using equation 7, 3.848 and 3.817 kJ/kg·K. Thermal diffusivity can then be determined using:

\[ \alpha = \frac{k}{\rho c_p} \]  

where \( \alpha \) is the thermal diffusivity (m²/s), and \( \rho \) is the mass density (kg/m³). Using equations 4 and 6 to estimate thermal conductivity and specific heat, the predicted thermal diffusivities for batch- and continuous-processed masa by-products were, respectively, 1.43 \( \times 10^{-7} \) and 1.41 \( \times 10^{-7} \) m²/s. These values were all very similar to those for water, which was not unexpected, due to the high moisture contents of the masa by-product samples. Still, a future investigation of measured thermal properties would be very beneficial to verify the predicted estimates.

**Nutritional Properties**

**Proximate Composition.** The proximate compositions of dry masa by-products are shown in table 1, and are vital for the assessment of the suitability of masa by-products as livestock feed additives. The results show that for both processes, the by-products are low in both protein and fat, moderate in ash content, and high in carbohydrate content. Jurgens (1988) has outlined nutritional requirements for various livestock diets. Growing and finishing swine (18 to 109 kg in body mass) require 13 to 15% crude protein in their rations; growing and finishing beef cattle (300 to 400 kg) require 10.6 to 13.5% crude protein; growing and finishing sheep (25 to 50 kg) require 12.9 to 17.2% crude protein; and poultry require 14.0 to 23.2% crude protein. Consequently, to effectively utilize masa by-products as a livestock feed source, a high-protein supplemental material, such as soybean meal, should be used in addition to the masa by-products for the development of a feed ingredient.

**Fiber Composition.** The fiber composition results are shown in table 1. Carbohydrates in organic materials consist of nitrogen-free extract and crude fiber. Nitrogen-free extract contains soluble sugars and starches, which are easily digested by livestock. Crude fiber, on the other hand, consists of cellulose and hemicellulose (which can be digested only by ruminant animals due to microflora in the rumen) and lignin, which is essentially indigestible. Ruminant microflora produce cellulase, the enzyme necessary to digest cellulose. Neutral Detergent Fiber (NDF) consists of cell wall materials, provides a measure of the total cellulose, hemicellulose, and lignin content of a material, and can be used as an indicator of voluntary feed intake for livestock. Acid Detergent Fiber (ADF) provides a measure of total cellulose and lignin content of a material.
(Jurgens, 1988). Utilizing the above relationships, it was determined that the hemicellulose contents of batch- and continuous-processed masa by-products, respectively, were 24.06 and 20.82% (d.b.), and the cellulose contents, respectively, were 30.55 and 31.83% (d.b.). Masa by-products are high in cellulose and hemicellulose and are low in lignin, and therefore would be well suited for use as potential feed ingredients for ruminant animals, which can digest these fibrous materials.

**Mineral Composition.** The mineral compositions of dry continuous-processed masa by-products are shown in table 1. Of all minerals studied, calcium occurred in the greatest quantity, with a mean value of 4.68% (d.b.), which accounted for 26.9% of all ash material in the dry masa by-product. The remaining minerals studied—potassium, magnesium, and phosphorus—combined, accounted for only 4.4% of all ash in the dry by-product. These results suggest that masa by-products are a potential source of both calcium and fiber for livestock diets. However, because substantial variability occurred in the data, it would be beneficial to conduct a further study of mineral content.

**Amino Acid Composition.** The amino acid compositions of dry continuous-processed masa by-products are shown in table 2. Even though corn masa by-products are low in protein content, the protein which is present is rich in the essential amino acids leucine and proline, and in the nonessential amino acids alanine, asparagine, glutamine, and glycine. However, masa by-products are low in the essential amino acids arginine, histidine, and methionine, and in the nonessential amino acid tyrosine.

**Property Relationships**

The relationships between the 15 measured physical and nutritional properties in the study were investigated using a correlation analysis of the mean property values for each sample. Fifteen of the resulting Pearson product-moment correlations (Speigel, 1994) were significant (p < 0.05) (table 3). The remainder of the correlations were not. The correlation coefficient (r) quantifies the strength of the linear relationship between two variables, and as shown in the table, eight of the variable combinations in the study had resulting correlation coefficients greater than 0.80 and thus exhibited fairly strong linear relationships. The most highly significant correlations occurred between L and b (r = 0.978), L and Fat Content (r = –0.944), and b and Fat Content (r = –0.905), and thus warrant further exploration.

To further investigate the relationships and interactions between the masa by-product properties, a principal components analysis was conducted on the 15 measured properties using the mean property values for each sample. Principal components analysis is used to reduce the dimensionality of multivariate data by summarizing the variance in the data and projecting it into a set of uncorrelated orthogonal linear combinations of the original variables. For this study, these linear combinations, or principal components, have the form:

\[ y_{PC} = a_1X_1 + a_2X_2 + \ldots + a_{15}X_{15} \] (9)

where \( y_{PC} \) is a principal component value, or score, \( a_1 \) through \( a_{15} \) are the principal component coefficients (i.e., eigenvectors), and \( X_1 \) through \( X_{15} \) are the original property variables that were measured in the study (Everitt and Dunn, 1991). The results for the principal components analysis are presented in table 4, which shows the eigenvectors and eigenvalues for the first five principal components. The first five principal components accounted for 92.6% of the total variability in the data, and thus provide a convenient and comprehensive summary of the information contained in the original 15 property variables, utilizing a reduced dimensionality of only five variables. Although the interpretation of principal components is very subjective, the first principal component appears to be an indication of material structure, while the second principal component appears to be an indication of chemical composition. Another advantage in using principal components analysis to summarize data is the ability to easily identify outliers, through examination of scatterplots of the calculated principal component scores. Using this approach, it was determined that an outlier did occur in the continuous-process by-product data. This outlier was produced by two yield stress readings that were somewhat lower than the typical yield stress values for the by-product materials, and might indicate a possible difference in material structure due to the continuous-cooking process. Even though the current study has been fairly extensive, it would be useful to further investigate these relationships and interactions.


Microsoft Excel v. 5.0a. 1993. Redmond, Wash.: Microsoft Corp.


