Alkaline Processing (Nixtamalization) of White Mexican Corn Hybrids for Tortilla Production: Significance of Corn Physicochemical Characteristics and Process Conditions[1]

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ABSTRACT

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Five white corn hybrids were processed (nixtamalized) using 10 different processing conditions; tortillas were prepared to establish relationships between corn composition, physical characteristics, and nixtamalization process or product properties. Corn hybrids were characterized by proximate analysis and by measuring Stenvert hardness, Wisconsin breakage, percent floaters, TADD overs, thousand-kernel weight, and test weight. Corn characteristics were correlated with process and product variables (effluent dry matter loss and pH; nixtamal moisture and color; masa moisture, color, and texture; and tortilla moisture, color, and rollability). Process and product variables such as corn solid loss, nixtamal moisture, masa texture, and tortilla color were influenced not only by processing parameters (cook temperature, cook time, and steep time) but also depended on corn characteristics. Significant regression equations were developed for nixtamalization dry matter loss ($P < 0.05$, $r^2 = 0.79$), nixtamal moisture ($P < 0.05$, $r^2 = 0.78$), masa gumminess ($P < 0.05$, $r^2 = 0.78$), tortilla texture ($P < 0.05$, $r^2 = 0.77$), tortilla moisture ($P < 0.05$, $r^2 = 0.80$), tortilla calcium ($P < 0.05$, $r^2 = 0.93$), and tortilla color a value ($P < 0.05$, $r^2 = 0.87$).

It is generally recognized that corn physical characteristics are important factors influencing the nixtamalization process and product characteristics (Rooney and Suhendro 1999). Processors adjust nixtamalization variables such as cook temperature, cook time, steep time, and lime concentration depending on a corn's physical characteristics to produce acceptable products.

Almeida-Dominguez et al (1997) related alkaline cooking properties of corn with grain characteristics and Rapid Visco Analyser (RVA) pasting properties. These researchers observed that properties such as water uptake during nixtamalization could be indirectly monitored with RVA properties in combination with percent floater values of the corn hybrid. In their study, RVA data complemented with corn hardness data was used to predict alkaline cooking properties; however, the results were based on nixtamalization of only 100-g samples at boiling temperatures. Rooney and Serna-Saldivar (1987) reported that corn hybrids with "hard" or corneous-vitreous endosperm texture often require longer cooking. Ellis et al (1983) observed that harder corn hybrids usually cook in a more predictable fashion than "soft" or floury corn. Jackson et al (1988), while investigating the effect of broken kernels on nixtamalization, observed that alkaline cooking-steeping time and product yields depend on the corn cultivar used for nixtamalization.

Corn kernel hardness characteristics have also been related to the magnitude and composition of corn solids loss in nejayote and wash water during nixtamalization (Pflugfelder et al 1988). These researchers noted that during commercial nixtamalization, loss of starch, proteins, and lipids in the effluent stream increased when softer corn was processed. Cortéz and Wild-Altamirano (1972) related tortilla quality to corn characteristics and observed that corn with greater moisture, hardness, and density produced the best tortillas.

Relationships between corn kernel characteristics and nixtamalization process and product variables have, largely, emerged as general observations based on experience. Only limited scientific data correlates corn characterization tests with process and product variables for corn processed using a range of processing conditions.

Traditionally, corn is nixtamalized by following several different cooking and steeping regimes. Small processors, in order to reduce energy costs, usually cook the corn for a shorter time, preferring a long steep. On the other hand, large processors using large-batch or semicontinuous cooking and steeping expedite nixtamalization by cooking rapidly at elevated temperatures followed by quenching; steep and overall process times are thus reduced.

The present study was conducted in an effort to elucidate significant relationships between corn composition, standardized corn characterization tests, and nixtamalization process or product parameters. This study reports relationships between corn characterization tests such as Stenvert hardness, Wisconsin breakage, percent floaters, thousand-kernel weight or test weights, and nixtamalization process-product parameters such as nixtamal moisture, nejayote and wash water pH, corn solid loss, masa and tortilla moisture and color, and masa and tortilla texture.

To quantify any product-process relationships, five white corn hybrids grown for tortilla manufacture in different regions of Mexico were selected for nixtamalization and tortilla production. The five hybrids were nixtamalized at 10 different cook-steep conditions (a total of 50 nixtamalization trials) using pilot-scale or near commercial-scale nixtamalization and tortilla manufacturing equipment. The hybrids were nixtamalized at 10 different cook-steep conditions to evaluate a wide spectrum of possible cook time and temperature and steep time combinations.

MATERIALS AND METHODS

Corn Samples

Five samples of white corn (*Zea mays* L.) grown in Sinaloa, Veracruz, Chiapas, Chihuahua, and Jalisco, Mexico (coded as MC1–MC5, respectively) were used for the nixtamalization experiments. These corn hybrids are cultivated primarily for traditional nixtamalization and tortilla production in Mexico. The corn was field-dried, bagged, and shipped by truck from its source to Lincoln, NE, and then each sample was aggregated, commercially cleaned, and rebagged at FlatWater Mills (Hastings, NE). All samples were stored in a freezer (maintained at –18°C), and equilibrated to room temperature before nixtamalization and analysis.

Corn Characterization

Each corn sample was characterized using tests described by Shandera et al (1997). Composite corn samples were collected for each corn type. Corn (≈200 ± 10 g) was removed from each of 15 bags (22.5 kg/bag) and combined to form the composite sample. TADD losses were calculated as % loss of kernel material after

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abrading 40 g of maize in a Tangential Abrasive Dehulling Device (model 4E-220; Venables Machine Works, Saskatoon, SK, Canada) for 10 min while suctioning off abraded material as described by Reichert et al (1986).

The Stenvert Hardness test involved grinding 20 g of maize using a microhammermill (GlenMills model V fitted with a 2-mm screen) at 360 rpm. The heights of soft endosperm and total ground material collected in the recovery tube, time to grind, reduced hammermill rpm at maximum grinding power, and quantity of hard endosperm recovered over a 425-µm sieve were measured (Pomeranz et al 1985). Corn breakage susceptibility was determined using a Wisconsin breakage tester (model 9/84, serial no. C0220, 1,800 rpm) as described by Watson and Herum (1986) and Pomeranz et al (1986).

Thousand-kernel weight was determined by hand-counting 100 whole kernels of each sample × 10. Floaters were determined as percent buoyant kernels immersed in a 31.3 Baume sodium nitrate solution maintained at 60°C, corresponding to a specific gravity of 1.275 (Peplinski et al 1989). Hardness index class was determined from the percent floaters and moisture content graph.

For proximate analysis, corn samples were ground first in a burr mill (Buhler, Minneapolis, MN) and subsequently finely ground using a sample mill (Udy Corp., Ft. Collins, CO). Corn moisture (ground sample) was determined by Approved Method 44-15A (AACC 2000). Corn protein content (N × 6.25) was determined by the Kjeltec procedure (Tecator, Inc., Herndon, VA) based on AACC Approved Method 46-12. Fat content was determined by the AOAC 960.39 soxtec procedure (model HT 1043 extraction unit and soxtec system model HT 1046 service unit; Tecator). Ash content in corn was calculated using AACC Approved Method 08-01, whereas crude fiber content was determined according to AOAC method 962.09 (FiberTec System; model M 1020 hot extractor and model 1021 cold extractor; Tecator, Inc.). Calcium content in the ground sample was analyzed by atomic absorption spectrophotometry AACC method 40-70.

TABLE I
Nixtamalization Conditions Used for Five Corn Hybrids

Condition	Cook Water (°C)	Holding Time (min)	Steep Time (hr)
1	80.3	35.0	4.6
2	83.0	20.0	12.4
3	83.0	50.0	12.4
4	89.0	13.8	4.6
5	89.0	35.0	0.7
6	89.0	35.0	8.5
7	89.0	35.0	16.3
8	89.5	56.2	4.6
9	96.0	20.0	12.4
10	98.7	35.0	4.6

All the above physical and chemical analyses were conducted in triplicate; means with standard deviations are reported. The data was statistically analyzed using NCSS statistical software (NCSS 2000; Visual Statistical Systems, Kaysville, UT).

Nixtamalization Procedure

All the experimental trials were conducted with 30 kg of corn using pilot-scale or near commercial-scale nixtamalization and tortilla baking equipment. For nixtamalization, 150 kg of water was weighed accurately and pumped into a gas-fired horizontal cook-steep tank (model OCT002-01; Lawrence Equipment, So El Monte, CA). Lime (300 g of $Ca(OH)_2$; Mississippi Lime Co., Alton, IL) was added to the cooking tank and mixed until dispersed. The tank was covered with a lid and the lime solution heated to the desired temperature. The corn (30 kg) was next added to the tank. The corn was gently stirred periodically (5–6 min) using a traditional wooden ladle or paddle to ensure a uniform temperature in the vessel. Due to the addition of room-temperature corn to preheated water, the temperature of the cooking tank declined ≈5–10°C. Heating was continued until the temperature of the corn-water-lime mixture recovered to the specified cooking temperature; cooking time was started then. Cooking temperatures were maintained thermostatically.

Corn was cooked with the tank covered with a lid. Covering the tank during cooking conserved water because vapor loss was reduced. The water temperature also reached the desired cooking temperature more rapidly after addition of corn, and temperatures could be maintained with less fluctuation.

At the end of cooking, the cooking tank lid was removed and steeping started for the required time. Steeping was terminated by draining the nejayote. Nixtamal was washed twice using 50 L of water per wash. For each wash, the water was poured into the cooking tank from a graduated cylindrical drum. Nixtamal was manually vigorously stirred in the wash water with a wooden paddle for ≈5 min and, at the end of the two washings, drained for ≈20 min by inclining the tank at an angle of ≈20° before the cooked corn was ground into masa. Nixtamal was ground into masa using a stone grinder (model OCG2000-01, Lawrence Equipment). The grinder setting was maintained at a constant gap for all the experimental

TABLE II
Compositional Characteristics of Five (Unprocessed) Corn Hybrids[a]

Constituents (%)	MC1	MC2	MC3	MC4	MC5
Protein	9.33 (0.09)	9.84 (0.04)	9.68 (0.14)	9.31 (0.03)	9.19 (0.19)
Crude fiber	1.86 (0.02)	1.94 (0.03)	2.01 (0.01)	2.42 (0.10)	1.87 (0.01)
Fat	6.56 (0.31)	4.57 (0.48)	5.03 (0.01)	3.74 (0.10)	4.79 (0.04)
Ash	1.87 (0.02)	1.31 (0.009)	1.38 (0.05)	1.20 (0.02)	1.73 (0.12)
Calcium	<0.01 (0.0007)	0.01 (0.0070)	0.04 (0.0020)	0.02 (0.00020)	0.03 (0.0051)
Moisture	10.20 (0.02)	10.71 (0.20)	11.80 (0.053	12.72 (0.04)	11.17 (0.04)

[a] Values in parentheses indicate standard deviations.

TABLE III
Physical Characteristics of Five (Unprocessed) Corn Hybrids[a]

Characteristics	MC1	MC2	MC3	MC4	MC5
Wisconsin breakage test (%)	37.55 (2.01)	26.47 (0.27)	25.46 (1.95)	19.81 (0.93)	18.44 (1.48)
TADD hardness test (%)	49.26 (1.03)	51.05 (1.69)	45.76 (1.57)	43.11 (1.40)	54.12 (1.03)
Stenvert hardness test (%)	69.58 (0.90)	69.47 (0.52)	69.93 (0.33)	74.31 (0.93)	68.53 (0.91)
Floaters (%)	16.00 (1.21)	28.00 (0.46)	28.67 (1.08)	32.00 (0.98)	36.67 (0.57)
Hardness index	4	3	3	4	3
Test weight (kg/hL)	78.7 (0.18)	75.9 (0.24)	75.2 (0.25)	76.6 (0.19)	76.4 (0.22)
Thousand-kernel weight (g)	348.3 (1.40)	282.2 (1.81)	272.8 (1.19)	268.1 (1.96)	332.9 (2.21)

[a] Values in parentheses indicate standard deviations.

trials. The water flow rate during grinding was set on a flow meter to 600 ± 10 mL/min and was maintained constant for all experimental trials. Ground nixtamal was molded into masa pats for tortilla preparation.

Small pats of masa were kneaded by hand and fed into tortilla sheeting and cutter rollers (model OFD1002-02, Lawrence Equipment). The tortillas were baked in a gas-fired, three-pass, continuous tortilla baking oven (model OPO1004-07, Lawrence Equipment) maintained at 321°C (700°F). After baking, tortillas were passed through a cooling conveyer (model OCC1208-03, Lawrence Equipment), collected at the end of the cooling rack, and placed in reclosable plastic bags. Some tortillas were immediately used for textural evaluation. Additional samples were frozen (–18°C) pending additional analyses.

Analysis of Nixtamal, Masa, and Tortillas

Moisture contents in nixtamal, masa, and tortillas were determined by AACC Approved Method 44-15A. To estimate the total effluent dry matter loss (DML), solids in nejayote and wash water were determined separately. Representative samples of 8 L each of nejayote and wash water were collected. Subsamples (200 mL) were removed in duplicate into preweighed aluminum pans. The pans were dried for 12 hr in a forced-air oven maintained at 103°C. Total DML was calculated based on the initial (30 kg) uncooked corn and reported as percent DML in nejayote and wash water. The pH of nejayote and wash water was also recorded using a pH meter.

Nixtamal, masa, and tortilla color characteristics (L, a, and b values) were evaluated in triplicate using a chromameter (CR-300, Minolta Corp., Ramsey, NJ) and average values reported.

Texture Analysis of Masa and Tortillas

Textural characteristics of masa were determined using a TA.XT2 texture analyzer (Texture Technologies Corp., Scarsdale, NY and Stable Micro Systems, Godalming, Surrey, UK). Texture profile analysis of fresh masa was conducted to measure masa hardness, firmness, adhesiveness, cohesiveness, chewiness, gumminess, and springiness following manufacturer’s instructions.

Tortilla texture was evaluated by measuring objective tortilla rollability on the texture analyzer as described by Suhendro et al (1998). The force required to roll a tortilla around a cylinder was measured, and peak force as well as peak work area calculated. Measurements were made immediately after tortilla production and after 24 hr of storage at room temperature.

Experimental Design and Statistical Analysis

The five corn hybrids were separately cooked using nixtamalization conditions (Table I). The study was initially designed as five separate response surface studies (hybrid design) with an objective of optimizing tortilla yield in each case (data not presented). In the RSM design, process variables (cook time, cook temperature, and steep time) were varied around a midpoint while concentration of lime was maintained at 1% of corn weight. Data from 10 nixtamalization conditions under which tortillas could successfully be produced were selected for analysis. The data presented here represent a total of 50 nixtamalization trials that were conducted for the five corn hybrids at 10 nixtamalization conditions (Table I). The data, therefore, represent a standardized range of process conditions centered around a midpoint (89°C cook temperature for 35 min with a steep time of 12 hr).

Stepwise regression analysis was used to find significant independent variables that influenced nixtamalization variables and product characteristics. Multiple regression analysis was used to develop equations describing changes in process and product variables with independent variables (cook and steep variables and corn characteristics). Regression equations have been reported for variables exhibiting $r^2 > 0.75$; otherwise, significant independent factors were listed. The variables with the greatest effect on r^2 values are listed first (in order) for each equation.

RESULTS AND DISCUSSION

Corn Characterization

The proximate composition of the corn samples is given in Table II. The results of various hardness and characterization tests conducted for the five corn hybrids are listed in Table III. All corn samples had a protein content of 9.2–9.8%, whereas the fat content varied at 3.7–6.5%. Corn sample MC2 had the highest protein content and sample MC1 exhibited the highest fat level. Corn sample MC4 showed the highest level of crude fiber (2.4%) but the lowest level of ash (1.2%).

The Wisconsin breakage test provides a measure of corn hardness when corn kernels are subjected to a centrifugal shattering force (Watson and Herum 1986). It is considered a relative measure of susceptibility to shipping damage. Corn with extensive internal cracks usually gives a higher Wisconsin breakage result (Pomeranz et al 1986). Corn Sample MC1 exhibited the highest Wisconsin breakage value (37.6), whereas samples MC4 and MC5 gave relatively low values of 19.8 and 18.4, respectively.

The TADD hardness test provides an estimation of material removed when corn kernels are subjected to a tangential abrasive force (Reichert et al 1986). Corn with soft endosperm usually has higher TADD losses as compared with hard-endosperm corn. TADD hardness test characterized corn sample MC4 as the hardest and sample MC2 as the softest.

None of the corn samples except MC4 showed significant variability in Stenvert hardness values. Sample MC4, with a value of 74.3, was the hardest of all the hybrids as evaluated by the Stenvert hardness test.

Floater values are a measure of apparent corn density (Shandera et al 1997). Hybrids MC5 and MC4, with floater values 36.6% and 32.0%, respectively, were relatively less dense compared with other samples. Sample MC1, with 16% floaters, exhibited the highest kernel density. Test weight is the weight of a known volume of corn (kg/hL). Test weight values observed for the corn samples were 75.2–78.7 kg/hL. The highest test weight was observed for MC1.

The thousand-kernel weights obtained for the corn samples were 268.1–348.3 g. Hybrids MC1 and MC5 exhibited relatively high thousand-kernel weight values compared with the other samples.

There was no consistent relationship in the various corn characterization tests and corn hybrids, indicating that each test measured a different physical characteristic. A high degree of negative correlation ($P < 0.001$, $r = 0.98$) was observed between Wisconsin breakage values and percent floaters. A significant negative correlation ($P < 0.05$, $r = 0.84$) was also observed between Stenvert hardness and the TADD hardness values. The hardness characterization tests were also significantly correlated with compositional characteristics. The Wisconsin breakage test values were positively correlated with fat content ($P < 0.001$, $r = 0.87$), and Stenvert hardness test values were positively correlated with corn crude fiber ($P < 0.001$, $r = 0.98$). Test weights showed a significant negative correlation with corn calcium ($P < 0.001$, $r = 0.76$). The thousand-kernel weight values were highly positively correlated with corn ash ($P < 0.001$, $r = 0.97$). When compared with the softer corn hybrids typically produced in the corn belt, these samples would all be considered hard and ideal for nixtamalization (Shandera et al 1997).

Nixtamalization DML

Stepwise regression analysis indicated that DML was significantly dependent on cook temperature, cook time, steep time, Wisconsin breakage, and hardness index class ($P < 0.05$, $r^2 = 0.79$). DML could be estimated using the regression equation:

$$\begin{gathered}\text{DML (\%)} = 0.135\ \text{(cook temperature)} + 0.034\ \text{(cook time)} \\ +0.06\ \text{(steep time)} + 0.05\ \text{(Wisconsin breakage test value)} \\ - 0.474\ \text{(hardness index class)} - 7.13\end{gathered}$$

Pflugfelder et al (1988) studied DML in commercial masa production and observed that starch, protein, and lipid loss were higher when softer corn was nixtamalized. These researchers concluded that corn with a soft crown and a floury endosperm resulted in higher solids loss. However, no significant correlation between corn characteristics and DML was presented. Serna-Saldivar et al (1991) have reported only a poor negative correlation ($r = -0.32$) between extent of corn pericarp removal and hardness. Their correlations between pericarp removal and thousand-kernel weight, test weight, and kernel density were also not significant. However, these researchers have concluded that, overall, softer kernels lost pericarp more thoroughly than harder hybrids. Jackson et al (1988) extensively investigated alkaline processing properties of stress-cracked and broken corn and observed that DML during nixtamalization was directly correlated with visually checked cracked-kernel count. These researchers also observed that the Wisconsin breakage test value was a good measure of stress-cracked kernel count. Dependence of DML on Wisconsin breakage values is also evident from our present study, even with the absence of extensive stress cracking (data not shown).

Nixtamal Moisture

Stepwise regression analysis indicated that, besides cook temperature, cook time, and steep time, corn calcium content and thousand-kernel weights were other significant factors influencing nixtamal moisture ($P < 0.05$, $r^2 = 0.78$). Nixtamal moisture was described by the regression equation:

$$\begin{gathered}\text{Nixtamal Moisture (\%)} = 24.36 + 0.29\ \text{(cook temperature)}\\ + 0.089\ \text{(cook time)} + 0.15\ \text{(steep time)} - 53.7\ \text{(corn calcium)}\\ - 0.017\ \text{(thousand-kernel weight)}\end{gathered}$$

It is generally believed that a critical level of water absorption during nixtamalization cooking and steeping is essential for obtaining optimum masa texture. Gomez et al (1991) observed that the desired nixtamal moisture target should be 48–50% because the resulting stone ground masa has acceptable plasticity, cohesiveness, and machinability. Serna-Saldivar et al (1993) concluded that nixtamal moisture content must be precisely controlled for specific applications, and recommended nixtamal moisture of 50–51% for table tortillas and 46–48% for tortilla chips. Although perhaps somewhat subtle, it is evident from the above equation that samples with low calcium content and low thousand-kernel weight values imbibed more water for given cook and steep nixtamalization conditions.

Nejayote and Wash Water pH

Nejayote pH was significantly dependent on corn cook temperature, cook time, steep time, percent floaters, and thousand-kernel weight ($P < 0.05$, $r^2 = 0.60$). Nejayote pH is influenced by the level of corn calcium uptake during nixtamalization. As the corn absorbs more calcium, nejayote pH gradually falls to become less alkaline (Trejo-Gonzalez et al 1982). It appears that, besides processing conditions, corn physical characteristics (floaters percent and thousand-kernel weight) influenced calcium uptake by the corn kernels. There was, however, little difference in wash water pH between the different treatments and corn hybrids. Wash water pH exhibited a poor correlation ($P < 0.05$, $r^2 = 0.43$) with process variables (cook temperature, steep time, and corn protein content).

Masa Texture

Several masa textural attributes (hardness, gumminess, and adhesiveness) were significantly influenced by nixtamalization conditions and corn characteristics. Cook temperature, cook time, TADD value, and thousand-kernel weight were significant factors influencing masa hardness ($P < 0.05$, $r^2 = 0.67$). Masa hardness was influenced by the hardness of corn; softer masa was produced when softer corn (high TADD values) was cooked at a higher temperature for a longer time. Nixtamalizing dense corn kernels exhibiting higher thousand-kernel weights, however, produced a hard masa texture.

Masa gumminess was primarily dependent on cook temperature, steep time, corn calcium, Wisconsin breakage test, and corn hardness index class values ($P < 0.05$, $r^2 = 0.78$). Masa gumminess was described by the regression equation:

$$\begin{gathered}\text{Masa gumminess} = 3.45 - 0.96\ \text{(cook temperature)} - 1.27\ \text{(steep time)}\\ + 2{,}362.2\ \text{(corn calcium)} - 1.27\ \text{(Wisconsin breakage test)}\\ + 34.4\ \text{(hardness index class)}\end{gathered}$$

Masa adhesiveness was significantly dependent on cook temperature, cook time, steep time, TADD, and Stenvert hardness values ($P < 0.05$, $r^2 = 0.65$).

To obtain optimum masa texture for proper sheeting, it is imperative that masa should have sufficient cohesiveness to form tortillas without being too sticky. These observations suggest that softer corn hybrids (high TADD and Stenvert hardness values), if cooked at high temperature and steeped for a long time, result in a more adhesive but sticky masa.

Ramirez-Wong et al (1994) evaluated hardness of masa prepared from nixtamalized ASGROW 405 corn (cook temperature at 100°C) and established that hardness and adhesiveness were primarily influenced by cooking time, degree of grind, interaction of cook time and grinding, moisture level, and interaction of cooking time and moisture levels. It is well recognized that the key factors that influence nixtamal characteristics and all subsequent processing parameters are intrinsic corn characteristics such as hardness, stress cracks, and kernel density (Rooney and Suhendro 1999). It would not be an overstatement to conclude that, besides nixtamalization conditions, inherent corn characteristics such as corn hardness and corn composition are primary determinants of masa texture. Other factors such as nixtamal moisture after cooking and steeping as described by Ramirez-Wong et al (1994) are likely to be influenced by corn characteristics and can be categorized as dependent factors.

Masa Color Characteristics

Corn tortilla color is an important quality characteristic relative to consumer acceptability. When the same lime concentration is used, masa color *a* values were significantly dependent on steep time, corn protein, and hardness index class values ($P < 0.05$, $r^2 = 0.79$) and could be described by the regression equation:

$$\begin{gathered}\text{Masa color } a \text{ value} = 0.013\ \text{(steep time)} + 1.3\ \text{(corn protein)}\\ - 0.29\ \text{(hardness index class)} - 11.69\end{gathered}$$

Masa color *b* values at the same lime concentration were significantly dependent on nixtamalization factors (cook temperature, cook time, steep time) and on corn test weights ($P < 0.05$, $r^2 = 0.62$).

Tortilla Texture

Tortilla rollability work area, evaluated using the texture analyzer, was influenced by corn characteristics as well as nixtamalization conditions. Work area was significantly dependent on cook time, corn ash content, TADD, and percent floater values ($P < 0.05$, $r^2 = 0.77$) and can be described by the regression equation:

$$\begin{gathered}\text{Tortilla rollability work area (Nm)} = 7.84\ \text{(corn ash.)}\\ + 0.39\ \text{(percent floaters)} - 0.21\ \text{(TADD value)}\\ - 0.054\ \text{(cook time)} - 10.08\end{gathered}$$

Rollability peak force, however, exhibited a poor correlation with process variables and corn characteristics, and was apparently independent of these factors. Suhendro et al (1998) inversely correlated work area with subjective rollability and flexibility scores. It appears that tortillas made from corn steeped for a longer time and using softer corn hybrids (high TADD losses) would have a more flexible texture; however, our data did not show this (significant) correlation.

Tortilla Moisture

Tortilla moisture is an important factor influencing product yield. The amount of tortilla moisture is likely to depend on baking conditions (baking temperature and time) as well as masa moisture. If similar amounts of water are added during grinding, masa moisture directly depends on nixtamal moisture. The moisture content of nixtamal or the amount of water absorbed by the corn during nixtamalization will be influenced by both nixtamalization conditions and intrinsic corn characteristics. Tortilla moisture was significantly influenced by cook temperature, cook time, steep time, and the Wisconsin breakage test ($P < 0.05$, $r^2 = 0.80$) and could be described by the regression equation:

$$\text{Tortilla moisture (\%)} = 24.89 + 0.25\ (\text{cook temperature}) + 0.067\ (\text{cook time}) + 0.138\ (\text{steep time}) - 0.36\ (\text{Wisconsin breakage test})$$

Tortilla Calcium

Tortillas are an important source of calcium among frequent tortilla consumers. The percent increase in calcium content from corn to tortillas (dry basis) was dependent on cook temperature, steep time, Wisconsin breakage test, and test weight ($P < 0.05$, $r^2 = 0.93$). The percent increase in calcium could be described by the regression equation:

$$\text{Percent increase in calcium} = 0.58\ (\text{cook temperature}) + 0.62\ (\text{steep time}) + 2.33\ (\text{Wisconsin breakage test}) + 12.52\ (\text{test weight}) - 1{,}052.8$$

It is apparent from the regression equation that tortillas prepared from softer corn cooked at a higher temperature and steeped for a longer time will retain more calcium. Trejo-Gonzales et al (1982) observed that, after 12 hr of steeping, the calcium content of the lime-treated corn grain was ≈4.5× that of the untreated grain. They concluded that calcium taken up by the corn grain during treatment bound to the starch granules; starch isolated from nixtamal had ≈3× more calcium than untreated corn. It appears that the cooking-steeping conditions and corn characteristics also significantly influence calcium uptake during nixtamalization.

Tortilla Color Characteristics

Tortilla color characteristics (L, a, and b values) were significantly dependent on nixtamalization as well as corn characteristics. Tortilla color a values were significantly dependent on steep time, corn fat, and protein content and hardness index class ($P < 0.05$, $r^2 = 0.87$). The a value could be described by the regression equation:

$$\text{Tortilla color } a \text{ value} = 0.028\ (\text{steep time}) + 0.065\ (\text{corn fat}) + 1.51\ (\text{corn protein}) - 0.35\ (\text{hardness index class}) - 13.59$$

Tortilla color L and b values significantly depend on cook temperature, steep time, and test weights ($P < 0.05$, $r^2 = 0.53$ and 0.48, respectively). Although tortilla color is an important property influencing acceptability, little information in the literature exists on how nixtamalization conditions or corn characteristics influence product color. It is evident from these observations that processing as well as corn intrinsic characteristics influence tortilla color. White corn with a higher test weight value appears more likely to produce a lighter and less yellow product.

CONCLUSIONS

A variety of tests, ranging from simple to sophisticated, are used by food processors to evaluate food corn properties for nixtamalization (Rooney et al 1995; Almeida-Dominguez et al 1997). In addition to federal grade, corn bulk density, floaters, true density, and stress-crack broken kernel percentages were determined to assess suitability for nixtamalization. Often, maize with a bright color, low stress cracks, and a hard kernel is preferred by alkaline processors (Rooney and Suhendro 1999). Most processors, however, rely on processing experience in selecting suitable hybrids. In this study, we have tried to establish nonempirical relationships between corn nixtamalization conditions, processing variables, and kernel characteristics with process product properties. It can be concluded that, although processing variables primarily affect nixtamalization and product characteristics (overall larger contribution to regression r^2 values), several factors, such as corn composition and hardness characteristics, critically influence nixtamalization. It is important to understand such relationships for proper selection of corn hybrids suitable for specific nixtamalization needs.

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