Polyphenolics and Antioxidant Capacity of White and Blue Corns Processed into Tortillas and Chips

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ABSTRACT

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White and blue corns of Mexican and American origins were lime-cooked to obtain nixtamals with optimal moisture (48–50%) for tortillas and chips. Blue kernels had less bulk density, softer endosperm and, consequently, required less cooking time than the white kernels. The optimum cooking regime for the white kernels was 100°C for 20 min, while the optimum for both pigmented genotypes was 90°C for 0 min (until the lime-cooking solution reached 90°C). Doughs, tortillas, and chips were characterized by total soluble phenolics (TSP), anthocyanins (ACN), and antioxidant capacity (AOX). A dough acidification procedure using fumaric acid (pH 5.2) was assessed as a means to improve TSP, ACN, and AOX retention. The Mexican blue corn had higher AOX (16%) than the American blue genotype, although the latter had a threefold higher TSP content (12.1 g/kg, dwb). Mexican and American blue corns had higher AOX capacity (29.6 and 25.6 μM trolox equivalents [TE]/g dwb), respectively, than the white corn (17.4 μM TE/g). White corns did not have detectable amounts of ACN, while blue Mexican and American kernels contained 342 and 261 mg/kg. Lime cooking had the greatest negative impact on the stability of TSP, ACN, and AOX. However, the acidification reduced ACN, TSP, and AOX losses by 8–23, 3–14, and 4–15%, respectively. Similar ACN losses were observed for both types of blue kernels when processed into nixtamal/dough (47%); however, ACN losses in tortillas and chips manufactured from the American blue genotype were higher (63 and 81%, respectively) than those of Mexican blue corn products (54 and 75%). ACN losses were highly correlated to TSP (r = 0.91) and AOX capacity losses (r = 0.94).

Anthocyanins, flavonoids, phenolic acids, and other polyphenols are phytochemicals, which are synthesized in the plant by primary or secondary metabolism. Although these compounds are considered to be nonnutritive, interest in antioxidant and bioactive properties has increased due to the various health benefits and nutraceutical effects (Setchell and Aedin 1999). Cumulative results of epidemiological, in vitro, and in vivo research suggest an inverse relationship between consumption and the incidence of various chronic and degenerative diseases including cardiovascular disease, urinary tract disorders, and various sorts of cancers. The health-benefiting properties of these plant metabolites have been related to high antioxidant and antiradical activities but also to many other mechanisms such as antimutagenic, estrogenic activities, inhibition of enzymes, and induction of detoxification enzymes (Skrede et al 2000; Adom and Liu 2002; Rondini et al 2002; Tsuda et al 2003; Fimognari et al 2004; Matsumoto et al 2004).

Several studies have reported the occurrence and diversity of polyphenolic compounds among various white corn genotypes and their pericarps, concluding that free forms and esters of ferulic and *p*-coumaric acids are the major phenolic compounds (Faulds and Williamson 1999; Kennedy et al 1999; Ostrabder et al 1999; Saulnier and Thibault 1999; Bily et al 2004). These polyphenolic derivatives are covalently bound to cell wall polysaccharides by UV-catalyzed cycloaddition or by oxidative coupling reactions or intracellular peroxidase and polyphenol oxidase systems (Faulds and Williamson 1999; Kennedy et al 1999; Ostrabder et al 1999; Saulnier and Thibault 1999; Bily et al 2004). The function of these compounds is to cross-link and strengthen the grain cell wall, therefore playing an important role in the lignification process that influences physical and textural attributes of plants and foods (Faulds and Williamson 1999; Kroon and Williamson 1999).

Red, blue, and purple-pigmented corn kernels are rich in anthocyanins; several reports have shown that cyanidin and peonidin glycosides are the main anthocyanins present in these kernels (Mazza and Miniati 1993; Bridle and Timberlake 1997; Pascual-Teresa et al 2002). Pigmented genotypes originated from the Peruvian Andes and were especially prized as ceremonial grain by the North American Indian tribes (Betran et al 2000; Rooney and Serna Saldivar 2003). Simple or acylated anthocyanin glycosides are mainly located in the endosperm's aleurone layer, greatly affecting the color of the grain. Kernels of small to medium size produce the darkest blue coloration because they possess a higher proportion of aleurone layer and are less diluted by the starchy endosperm (Betran et al 2000). Physical and flavor differences have also been observed among white and colored cultivars. For instance, blue corns have a floury or soft endosperm type that generally grows in long ears (8–12 rows) (Betran et al 2000). Due to polyphenols and other related compounds, blue corn products have a unique and characteristic flavor and currently have a special niche among organic and functional products (Rooney and Serna Saldivar 2003).

Nixtamalization, or lime-cooking, is the alkaline cooking of corn kernels in a calcium hydroxide solution. This process is responsible for important physiochemical, nutritional, and sensory characteristics of corn-based products including pericarp removal (Serna Saldivar et al 1990), calcium incorporation into kernels (Serna Saldivar et al 1991a,b, 1992), improvement in niacin bioavailability (Koetz and Neukom 1977), and formation of flavor and color compounds that impart special organoleptic characteristics to these products (Serna Saldivar et al 1990). Nixtamalization also affects polyphenolic derivatives by breaking down ester linkages, consequently releasing free phenolic forms into the cooking solution (Pflugfelder et al 1988; Saulnier and Thibault 1999; Cortes et al 2006). This alkaline chemical hydrolysis is responsible for the partial disintegration of the kernel's pericarp.

White dented corns, as well as blue and purple/red genotypes, are currently processed into instant flour for tortilla production, pregelatinized flours, tortillas, chips, extruded breakfast cereals, and snacks. Processing parameters for the production of these products significantly varies according to the physical properties of the kernels. As previously discussed, blue corn kernels have a softer endosperm than white counterparts used for lime cooking, consequently requiring less cooking and steeping (Rooney and Serna Saldivar 2003).

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Although previous reports have investigated the effects of nixtamalization on various quality and physicochemical attributes of corn products (Zazueta-Morales et al 2001, 2002; Gonzalez et al 2004; Cortes et al 2006), studies have yet to report the retention of polyphenolic and antioxidant capacity during the nixtamalization and the subsequent thermal processes needed to manufacture tortillas and chips. Therefore, the present study evaluated the levels of total soluble phenolics (TSP), total anthocyanins ACN), and antioxidant capacity content (AOX) of white and blue corns of Mexican and American origin during nixtamalization and subsequent thermal processing into tortillas and chips. An acidification strategy postnixtamalization was also evaluated as a means to improve the color and polyphenolic stability of these products because the alkaline conditions of nixtamalization are expected to negatively impact these factors.

MATERIALS AND METHODS

Corn Types

Commercial Mexican white corn with intermediate to hard endosperm texture used as a control was obtained in 2003 from Agroinsa (Guadalupe, NL, Mexico). These kernels are preferred by the tortilla industry. Two different blue genotypes with soft endosperm texture were obtained from Mexico and the United States in 2003. The Mexican blue corn originated from Toluca, Mexico, whereas the American blue corn was harvested in New Mexico. Test weight (expressed as kg/hL) was measured with a Winchester bushel meter (Seedburo Equipment, Chicago, IL) according to Approved Method 14-40 (AACC International 2000). Thousand-kernel weight was determined by weighing 100 randomly selected whole kernels. Endosperm texture was subjectively determined after bisecting 10 randomly selected kernels. The proportion of floury or chalky endosperm to corneous or vitreous endosperm was subjectively rated.

Lime-Cooking Trials

The lime-cooking properties of the three different corn genotypes were determined according to the nylon bag procedure described by Serna-Saldivar et al (1993). Samples (100 g) were placed in nylon bags and cooked at 90–100°C for 0 min (until they reached the desired temperature), 10 min, and 20 min in a steam-jacketed kettle containing 30 L of water with 100 g of lime (J.T. Baker Chemical, Phillpsburg, NJ). Resulting grains were steeped for 12 hr and then washed with tap water. Weights of cooked nixtamals before and after drying at 100°C for at least 12 hr were used to determine moisture and dry matter loss. Optimum cooking conditions were determined as those needed to produce a nixtamal with 48–50% moisture content, which is well suited for tortilla and chip production.

Production of Nixtamal, Tortillas, and Chips

Optimized conditions from the lime-cooking trial were used to produce nixtamals, tortillas, and chips from the white and blue corns. Briefly, 3 kg of white kernels were lime-cooked for 20 min at 100°C with 9 L of water containing 30 g of lime, whereas both blue-pigmented genotypes were cooked using the same calcium hydroxide solution but until the solution reached 90°C (reported as 90°C for 0 min). Nixtamals were then allowed to steep for 12 hr and were subsequently washed with tap water to remove the pericarp and excess lime solution. A coarse dough suitable for tortilla and chip production was then obtained by stone-grinding nixtamals with enough water to increase the moisture to ≈56% using a grinder equipped with a 10 HP motor and 22-cm lava stones (Fertitor, Puebla, Mexico). The resulting dough was then divided into two equal proportions (control and acidified) for subsequent evaluation. The acidified dough was prepared by adding sufficient fumaric acid (0.2 g of fumaric acid/100 g, dry corn weight) to reduce to pH 5.2. Doughs were then divided into 25-g pieces, pressed into tortilla disks, and baked on a hot griddle at 220°C for 1.5 min (30 sec each side, followed by 15 sec on each side). After baking, the tortillas were cut into four pie-shaped pieces and allowed to rest for at least 30 min before deep-fat frying (Hobart fryer, model HK 31-1, Troy, OH) at 175°C for 1 min. Resulting chips were blotted in paper towels to remove excess oil and allowed to cool for 20 min at room temperature. Samples of raw kernels, doughs, tortillas, and tortilla chips were placed in resealable plastic bags and immediately stored at –20°C.

Extraction Procedure

Triplicate samples from each treatment (100 g) were homogenized in 50 mL of methanol acidified with 0.01% HCl using a tissuemizer (PT-10, Brinkman Instruments, Westbury, NY). Resulting isolates were left overnight to allow complete extraction of polyphenols. Isolates were then diluted 10-fold with acidified water (0.1% HCl) and subsequently passed through previously activated Waters C_{18} Sep-Pak cartridges (Waters, Milford, MA) to fractionate polyphenols from polar compounds (sugars, organic acids, etc.). After washing the cartridge with two volumes of 0.01% (v/v) aqueous HCl, polyphenols were eluted with methanol acidified with 0.01% HCl (v/v).

Quantification of Total Soluble Phenols (TSP)

Total soluble phenols were determined using the Folin-Ciocalteau assay described by Swain and Hills (1959) with modifications introduced by Vinson et al (2001). The concentration of TSP (mg/kg) was reported as gallic acid equivalents.

Quantification of Anthocyanins (ACN)

Total monomeric ACN content was determined on appropriately diluted samples by the pH differential spectrophotometric method of Wrolstad (1976), and quantified as cyanidin-3-glucoside equivalents (extinction coefficient of 26,900 L/cm/mol, MW 449.2 g/mol). The method is based on the collection of absorbance readings at two values (pH 1 and 4.5) and at two wavelengths, including the maximum absorbance of the pigment (520 nm) and a turbidity correction at 700 nm.

Antioxidant (AOX) Capacity

Antioxidant capacity was determined using the oxygen radical absorbance capacity (ORAC) assay evaluated against a standard of trolox as described by Talcott et al (2003) with data expressed in trolox equivalents (TE/g, dwb). Isolates were diluted 10-fold in pH 7.0 phosphate buffer before pipetting into a 96-well microplate with corrections made for background interference due to the phosphate buffer and extraction solvent. All reagents were obtained from Sigma Chemical Co. (St. Louis, MO).

Instrumental Color Measurements

Hunter CIE color characteristics of ground tortillas and chips (L^* [lightness], a, and b) were measured using a chromameter (Minolta CR-300 series, Japan). Chroma, hue, and E values were calculated using three equations: Chroma = $(a^2 + b^2)^{1/2}$; Hue = $\tan^{-1} (b/a)$; and $E = (L^2 + a^2 + b^2)^{1/2}$.

Statistical Analysis

Data of the physical properties (bulk density and 1,000 kernel weight) and initial phytochemical levels (TSP, ACN, and AOX) of grains were analyzed as a single ANOVA that compared three corn genotypes (Mexican white, American blue, and Mexican blue). Data from the cooking trial was analyzed as a 3 × 3 bifactorial that compared three corn genotypes lime-cooked at three different times (0, 10, and 20 min). Data from phytochemical and quality analyses as affected by processing was analyzed as a 3 × 4 × 2 factorial that compared three corn genotypes processed into four products (raw kernels, doughs, baked tortillas, and fried tortilla chips) as influenced by a postnixtamalization acidification step (control and acidified). All experiments were randomized and conducted in triplicate. Multiple linear regression, ANOVA, and Pearson correlations were determined using JMP software, v. 5.0 (SAS Institute, Cary, NC); and mean separation used LSD ($P < 0.05$).

RESULTS AND DISCUSSION

Polyphenolic and Antioxidant Capacity of Raw Corn Kernels

Results showed that TSP content of different corn genotypes was inversely related to AOX capacity (Table I). The Mexican white corn had 2.8- and 8.4-fold higher TSP content than the American and Mexican blue corns, respectively, although the latter blue genotypes had 1.5 and 1.7-fold higher AOX capacity, respectively. Differences in AOX capacity between white and blue genotypes can be attributed to the presence of ACN in the pigmented corns, while differences between blue genotypes are possibly related to the concentration and specific composition of ACN derivatives such as simple or acylated glycosides of cyanidin, pelargonidin, or peonidin (Meyer et al 1998; Stintzing et al 2002). The specific occurrence and content of polyphenolics present in all genotypes such as catechin and free and conjugated forms of ferulic acid was another factor that likely influenced total AOX capacity (Kroon and Williamson 1999; Adom et al 2002). For example, previous studies have shown that on an equal molar ratio basis, free ferulic acid had lower AOX capacity than both the 5-5' and 8-5' dimmers and catechin (Garcia-Conesa et al 1999; Kroon and Williamson 1999; Adom and Liu 2002; Anselmi et al 2004). Moreover, factors such as polarity of the testing system, nature of radicals, and the type of substrate are known to influence the overall effectiveness of an AOX compound (Rice-Evans et al 1996; Del Pozo-Insfran et al 2004).

TABLE I
Initial Levels (dwb) of Total Soluble Phenolics, Total Anthocyanins, and Antioxidant Capacity in White and Blue Corns[a]

Maize Genotype	Total Soluble Phenolics[b] (g/kg)	Total Anthocyanins[c] (mg/kg)	Antioxidant Capacity[d] (μ*M* TE/g)
Mexican white	34.3a	nd[e]	17.4c
Mexican blue	4.1c	342.2a	29.6a
American blue	12.1b	260.9b	25.6b

[a] Values followed by different letters within columns are significantly different (LSD, $P < 0.05$).
[b] Expressed in gallic acid equivalents.
[c] Expressed as cyanidin 3-glucoside equivalents.
[d] Expressed in trolox equivalents.
[e] Nondetectable.

TABLE II
Physical Properties and Endosperm Texture of White and Blue Corns[a]

Maize Genotype	Bulk Density (kg/hL)	1,000 Kernel Weight (g)	Endosperm Texture
Mexican white	75.3a	349b	Intermediate-hard
Mexican blue	63.1c	382a	Floury
American blue	65.9b	320c	Floury

[a] Values followed by different letters within columns are significantly different (LSD, $P < 0.05$).

Results for total ACN were similar to those for AOX capacity; Mexican blue corn contained higher amounts of total ACN when compared with its American counterpart, which was likely attributable to environmental, seasonal, and geographical growing conditions (Kroon and Williamson 1999; Adom et al 2002).

Physical Properties of Corn Genotypes

As evidenced by bulk density and subjective endosperm evaluations, the Mexican white corn had a significantly higher bulk density and harder endosperm texture than both blue corn genotypes (Table II). However, Mexican blue corn had higher 1,000 kernel weight or grain size than the Mexican white corn and American blue corn. On average, both blue genotypes had 15% less bulk density than the white dent corn due to a higher ratio of soft or floury endosperm. Betran et al (2000) also reported that blue corns have a soft or floury endosperm that decreases production yield when compared with other commercial types of corn such as the white and yellow genotypes. Differences in endosperm hardness likely can be attributed to the specific polyphenolic composition of these corn genotypes, especially the presence of ferulic acid dimmers. Evidence indicates that these compounds cross-link and strengthen the grain cell wall, consequently playing a critical role in the lignification process that influences physical and textural attributes of corn kernels (Faulds and Williamson 1999; Kroon and Williamson 1999). Based on subjective endosperm evaluations, the Mexican white corn had the proportion of soft to hard endosperm recommended for tortilla production (Serna Saldivar et al 1990).

Lime-Cooking Properties

The purpose of this sub-study was to determine the optimal lime-cooking conditions (time and temperature) to achieve a nixtamal with 48–50% moisture. Evaluated temperatures of 90–100°C and

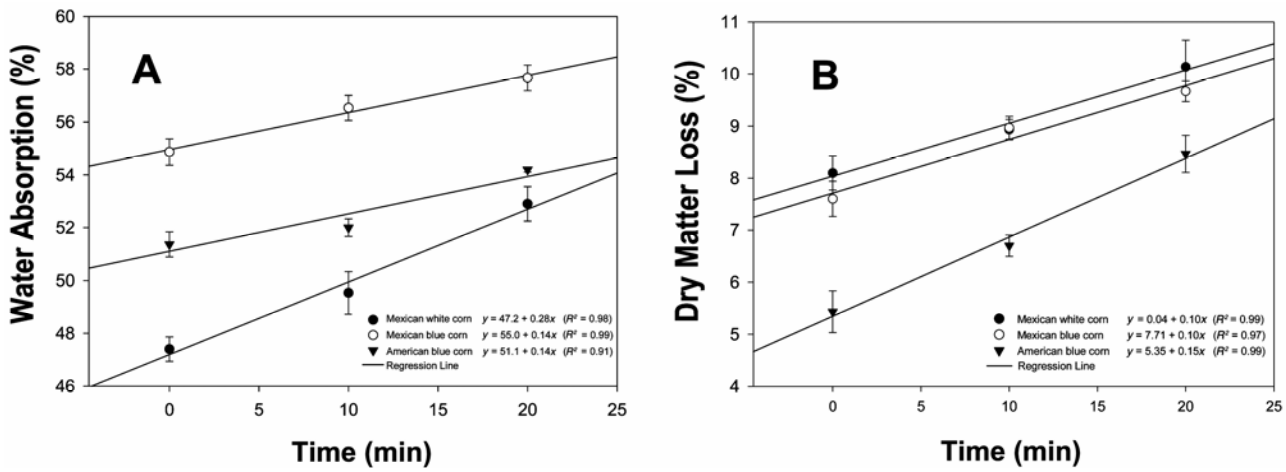

Fig. 1. Water absorption (**A**) and dry mater loss (**B**) during lime cooking of Mexican white corn (cooked at 100°C) and American and Mexican blue corns (cooked at 90°C) as affected by cooking time (min).

cooking times of 0, 10, and 20 min were used for all corn genotypes. Results showed that cooking temperatures between 90 and 95°C were sufficient for blue corns, while a temperature of 100°C (boiling temperature) was necessary for the white corn (data not shown). Results from subjective color evaluations showed a profound color loss when blue corns were alkali-cooked at temperatures >90°C. Presumably in parallel with these color changes was the increased degradation of polyphenolics and AOX capacity, given that polyphenolic stability decreases when present in alkaline conditions, especially when high temperatures are involved (Mazza and Miniati 1993; Bridle and Timberlake 1997). Based on these results, 90°C temperatyre was used to study the physical properties of the blue genotypes to obtain nixtamals and corn products with enhanced color, dough properties, and AOX retention.

In accordance with initial physical evaluations of the corn kernels, the Mexican white corn required higher temperature and longer cooking time conditions than both blue genotypes to obtain a nixtamal with the desired moisture content (Fig. 1A). The white corn required ≈20 min of cooking at boiling temperature to achieve 50% moisture, whereas the American and Mexican blue corns required a significantly lower thermal treatment (90°C for 0 min). It is well known that grains with a harder endosperm require more severe cooking conditions to enhance the penetration of the hot lime solution and pregelatinize the starch (Serna Saldivar et al 1991a,b). The higher time-temperature cooking conditions needed for the white corn might be related to its particular polyphenolic composition and content because evidence indicates that certain polyphenolics present in corn such as the dimmers of ferulic acid are responsible for strengthening the grain cell wall (Kroon and Williamson 1999; Bily et al 2004).

Results also indicated that the Mexican blue corn had higher water absorption (Fig. 1A) than its American counterpart, while dry matter loss (Fig. 1B) was similar between the Mexican blue genotype and the Mexican white genotype followed by the American blue genotype. Results also show that the rate of water absorption was more pronounced for the white genotype than for both blue corns, which was likely influenced by the combined effect of temperature and time used to cook the white grain.

Properties of Tortillas and Chips

According to the results observed from nixtamal weight (Table III), the Mexican blue corn absorbed the highest amount of lime solution during nixtamalization due to its softer endosperm texture, it was followed closely by the American blue corn and then by the Mexican white corn. The latter observation occurred even though the cooking times for both blue genotypes were adjusted according to results of the preliminary cooking trial. The American blue corn contained ≈52% moisture despite kernels cooked at a maximum temperature of 90°C for 0 min. After steeping and washing, white corn nixtamal contained the specified 48% moisture (Table III). The dough pieces lost 21–25% moisture during tortilla baking and 24–27% during deep-fat frying; these losses were insignificantly affected by the addition of fumaric acid. Independent of the corn genotype, the resulting chips contained <2% moisture after frying and cooling in accordance with previous reports (Serna Saldivar et al 1990; Rooney and Serna Saldivar 2003).

Processing Effects on Polyphenolic Content, Antioxidant Capacity, and Color

Lime cooking, in combination with the leaching of polyphenolics into the cooking solution, was the most detrimental unit operation to polyphenolic and AOX retention, while the effects of subsequent thermal steps of tortilla and chip production were not as pronounced. Moreover, the white corn underwent the most pronounced losses. Results also indicated that the proposed acidification strategy was instrumental in retaining higher levels of TSP, ACN, and AOX capacity in all corn products.

Although similar ACN losses were observed for both blue pigment genotypes when processed into nixtamals (≈47%) (Fig. 2), the American genotype underwent significantly higher degradation when processed into tortillas and chips. The proposed acidification procedure reduced ACN losses for both pigmented genotypes and it was most effective in preventing the losses that occurred in the Mexican blue genotype. Reduction of ACN losses by addition of fumaric acid were in the order of 8.1, 11.7, and 22.7% for doughs, tortillas, and chips produced with the Mexican corns, while losses were decreased by 3.9, 10.7, and 11.3% for nixtamal, tortillas, and chips produced with the American blue genotype. The higher stability of ACN present in the Mexican blue genotype without acidification can probably be attributed to the specific

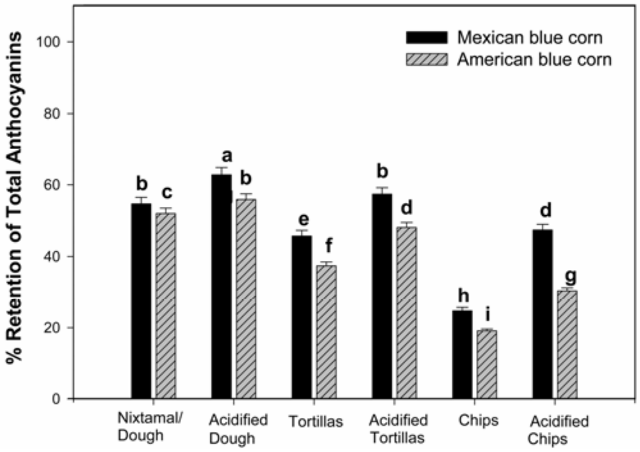

Fig. 2. Retention (%) of total anthocyanins in processed corn products (nixtamal, tortillas, and chips) as affected by origin (American or Mexican) and a postnixtamalization acidification of dough (reduction to pH 5.2). Retention (%) calculated from initial concentration in raw kernels. Bars with different letters for each processing treatment are significantly different (LSD, $P < 0.05$).

TABLE III
Effect of Acidification and Corn Genotype (Mexican White, American Blue, and Mexican Blue) on pH and Yield of Tortillas and Chips[a,b]

Treatment	Maize Genotype	Nixtamal pH	Nixtamal Weight[c] (kg)	Masa Weight (g)	Tortilla Weight (g)	% Wt Loss During Baking	Tortilla Chip Weight (g)	% Weight Loss During Frying
Nonacidified	Mexican white	6.93b	1.73c	20.3a	15.8a	22.2b	11.6ab	26.6a
	Mexican blue	7.45a	1.82a	20.3a	15.2b	25.1a	11.2b	26.1ab
	American blue	7.48a	1.78b	20.3a	15.8a	22.0b	12.0a	24.4b
Acidified[d]	Mexican white	5.11d	1.73c	20.3a	15.4b	24.0a	11.6ab	24.9ab
	Mexican blue	5.12d	1.82a	20.3a	16.0a	21.0b	12.0a	25.3ab
	American blue	5.48c	1.78b	20.3a	16.0a	21.2b	11.9a	25.6ab

[a] Values followed by different letters within columns are significantly different (LSD, $P < 0.05$).

[b] Corn kernels were cooked according to results obtained in the lime-cooking trial (100°C for 20 min for white corn, and 90°C for 0 min for both blue genotypes).

[c] Yield based on 1 kg of corn kernels. Mexican white, Mexican blue, and American blue corn kernels contained 11.1, 11.1, and 14.3% moisture, respectively.

[d] Acidified doughs were obtained by addition of fumaric acid to drop to pH 5.2.

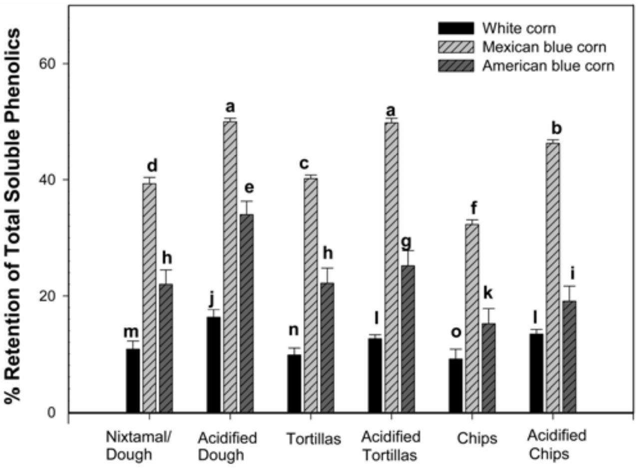

Fig. 3. Retention (%) of total soluble phenolics in processed corn products (nixtamal, tortillas, and chips) as affected by origin (American or Mexican) and a postnixtamalization acidification of dough (reduction to pH 5.2). Retention (%) calculated from initial concentration in raw kernels. Bars with different letters for each processing treatment are significantly different (LSD, $P < 0.05$).

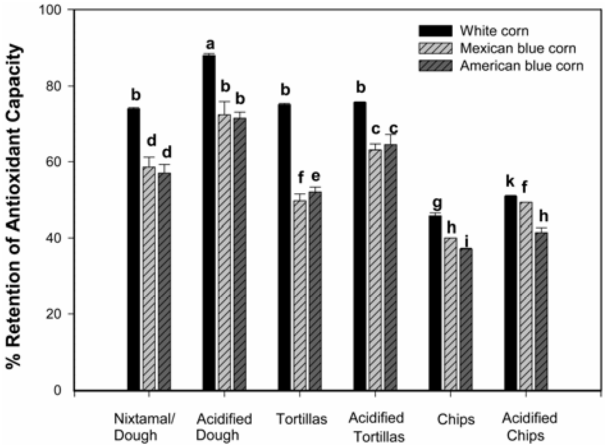

Fig. 4. Retention (%) of antioxidant capacity in processed corn products (nixtamal, tortillas, and chips) as affected by origin (American or Mexican) and a postnixtamalization acidification of dough (reduction to pH 5.2). Retention (%) calculated from initial ORAC values of raw kernels. Bars with different letters for each processing treatment are significantly different (LSD, $P < 0.05$).

occurrence of ACN derivatives or presence of other polyphenolic compounds in this genotype. Previous investigations have concluded that these factors have a profound effect on the processing and storage stability of anthocyanins (Mazza and Miniati 1993; Bridle and Timberlake 1997; Del Pozo-Insfran et al 2004). Independent of genotype and acidification treatment, ACN losses were highly correlated to polyphenolic content ($r = 0.91$) and AOX losses ($r = 0.94$).

TSP losses occurred for all corn gentotypes during lime cooking, yet losses were appreciably more pronounced for the white genotype. The Mexican white corn lost 90% of its initial TSP content, while the Mexican and American blue corns lost 61 and 78%, respectively (Fig. 3). The longer cooking time and higher temperature required to lime-cook the white genotype, as well as its specific polyphenolic composition, might be partially responsible for the higher losses. Further losses due to processing into tortillas and chips were practically insignificant for the white genotype (≤2%). However for the Mexican and American blue genotypes, frying was the main operation influencing TSP losses (7 and 10% additional losses, respectively). Acidification of the Mexican white corn dough only reduced TSP losses by 3% for all of its products, while acidification was effective in reducing TSP losses (≈11%) for all products manufactured with the blue pigment genotypes.

Contrary to the trends observed for losses of TSP, the blue corns underwent significantly higher AOX losses than the white genotype. On average, the nixtamals, tortillas, and chips produced from the blue corns lost 42, 49, and 62% of their initial AOX (Fig. 4), while the white genotype lost 25, 26, and 46% of its initial AOX, respectively. However, products manufactured from the blue genotypes still contained higher AOX (1.5–4.5 μ*M* TE/g) than their counterparts produced with the white corn. Independent from the acidification treatment, Mexican blue products contained the highest AOX. Dough acidification was again instrumental in reducing TSP and ACN degradation rates and, in this instance, reduced AOX losses by ≈12% following both nixtamalization and tortilla production and by 6% for chips.

Results from instrumental color evaluations (Table IV) were parallel to changes in ACN and TSP retention. White corn tortillas and their resulting chips presented the highest *L* and *E* values, values that were expected because of the absence of pigments. Hue angles obtained for white corn tortillas (95–96°) indicated a yellow color that became a darker yellow hue following the frying of the tortillas into chips (88–99°). The formation of brown pigments from the Maillard reaction is a common explanation for the colorimetric changes that take place during frying of tortilla chips (Buttery and Ling 1995).

Hue angles were the instrumental parameter that best described the color differences between both blue corn types and the effects of the acidification treatment (Table IV). Acidification decreased hue angles for both tortillas and chips, which suggest that the lower dough pH favored a purple hue over the burgundy-brown. Blue corn tortillas manufactured with the American corn presented a higher decline in hue angle (27.4°) as a result of acidification when compared with the decline observed for the Mexican blue corn tortilla (12°). From the hue angle locations in the color solid space, American blue corn tortillas may appear to the human eye as deeper purple color. However, frying resulted in significant changes in hue angles from a range of 6–358° for tortillas to 16–26° for the tortilla chips, suggesting the destruction of anthocyanins due to high processing temperatures. For both pigmented corn genotypes, acidification resulted in significantly lower hue angles, which can be interpreted as a better blue tortilla chip color (purple not burgundy). Based on hue angles alone, acidified tortillas manufactured with American blue corn genotype resulted in a better appearance (hue angle 339°). However, after frying, the acidified chips from the Mexican blue corn appeared to have the best visual appearance (hue angle 15.8°).

Chroma values increased when tortillas were fried into chips, indicating a decrease in the opaqueness of the tortilla surface, possibly caused by oil absorption and changes in the visual characteristics of starch and cell walls.

CONCLUSIONS

The Mexican and American blue corn genotypes had ≈15% less bulk density than the white dent corn due to their soft or floury endosperm texture and, consequently, absorbed more water during lime cooking. To obtain blue corn nixtamals with 48% moisture suitable for tortilla chips, the blue corns were cooked until the lime cooking solution reached a temperature of 90°C. The dough pieces lost 21–25% moisture during tortilla baking and 23.4–26.5 during deep-fat frying. The resulting chips contained <2% moisture after frying and cooling. Blue corn tortilla chips had approximately half of the *L* values and higher *a* and lower *b* values when compared with the control white tortilla chips.

TABLE IV
Instrumental Color Values of Tortillas and Chips Produced from Normal and Acidified Doughs of White and Blue Corns[a]

Corn Genotype	Acidification Treatment[b]	*L*	*a*	*b*	Hue[c]	Chroma[d]	*E* Value[e]
Tortillas							
Mexican white	No	67.3a	–1.8d	18.0a	96.0d	18.2a	69.7a
	Yes	66.8a	–1.6d	17.4a	95.3d	17.5a	69.0a
Mexican blue	No	40.0b	6.1c	–0.2b	357.6a	6.2c	40.4b
	Yes	34.4c	7.3b	–1.9c	345.5b	7.6bc	35.3c
American blue	No	32.0c	8.6a	0.9b	5.9e	8.7b	35.1c
	Yes	32.4c	8.2b	–3.2c	338.9c	8.8b	33.6c
Chips							
Mexican white	No	63.7a	0.0c	25.0a	90.0a	25.0a	68.5a
	Yes	62.0a	0.8c	25.8a	88.3a	25.8a	67.2a
Mexican blue	No	31.2b	9.2a	4.6b	25.9b	10.5bc	33.0b
	Yes	28.4b	7.9b	3.8bc	15.8c	8.3d	29.7b
American blue	No	31.9b	9.3a	4.9b	26.5b	10.7b	33.7b
	Yes	28.9b	8.2b	2.4c	24.4b	9.1cd	30.4b

[a] Values followed by different letters within columns are significantly different (LSD, $P < 0.05$).
[b] Acidified doughs were obtained by addition of fumaric acid to drop to pH 5.2.
[c] Hue = $\tan^{-1}(b/a)$.
[d] Chroma = $(a^2 + b^2)^{1/2}$.
[e] $E = (L^2 + a^2 + b^2)^{1/2}$.

Phytochemical degradation during processing was successfully assessed and significantly reduced following the proposed acidification strategy. Results showed that kernels and nixtamalized products obtained from the Mexican blue corn had higher AOX content than those produced from its American counterpart and the Mexican white genotype. These results were partially attributed to the high amounts of ACN present in the blue corns or to the particular polyphenolic composition. The dough acidification with fumaric acid not only reduced TSP, ACN, and AOX losses but also resulted in products with a more intense blue-purple coloration.

Results of this study can be used to increase the phytochemical content and functional properties of blue corn in a variety of food products, which is of interest due to the increasing consumer preference for corn-based products and for their possible contribution to the human diet owing to the antioxidant activity and potential nutraceutical properties.

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