Impact of different alkaline-heating processes on technological and nutritional properties of maize tortillas

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Summary

The effects of three different alkaline-cooking processes (gas-fired or traditional method, ultrasonic-bath and infrared heating) were evaluated on certain physicochemical, quality, compositional, nutritional and viscoamylographic properties of maize tortillas. All tortillas presented adequate physicochemical and quality characteristics for consumption. However, tortillas from infrared nixtamalization retained 25.1% and 32.7% more lipids, as well as 72.3% and 41.5% more tryptophan than traditional and ultrasonic-bath tortillas, respectively. The chemical composition of the nejayote from traditional, ultrasonic-bath, and infrared nixtamalization showed that the lost of maize solids was 3.1%, 3.5%, and 1.8% (w/w), respectively. During infrared nixtamalization 40.9% and 47.3% less of the total solids were lost as compared to traditional and ultrasonic-bath nixtamalization. Furthermore, tortillas from infrared nixtamalization presented the lowest value of starch retrogradation. According to these results, a novel and innovative nixtamalization procedure based on infrared heating was developed to produce tortillas with improved physicochemical, compositional, nutritional and pasting properties.

Keywords

maize; alkaline–heating processes; tortillas; technological properties, nutritional properties

Mexico, with an estimated population of 118.3 million people [1], has the highest world per capita consumption of maize. In 2011, the maize production was over 27.27 million metric tons, about 17.64 million of which were destined for human consumption, 9.61 million for feed, and the rest for seed use [2]. Mesoamerica landraces, varieties and hybrids are harvested all year around under diverse climatic conditions. Therefore, the growing, harvesting and postharvest handling vary between geographic zones, which affects the quality of maize-based products. The maize grains contain 7% to 13% protein (dry basis), but the quality of protein is deficient because zein, the main protein fraction, has low contents of the essential amino acids lysine and tryptophan [3]. Thus, the consumption of proteins with insufficient essential amino acids is a great problem in some areas of Mexico, principally where "regular" maize is the basic staple food.

In Mexico, maize is primarily consumed as tortillas, with a per capita consumption of about 120 kg per year [4]. These are traditionally made utilizing the ancestral alkaline-cooking process called nixtamalization. The traditional nixtamalization process (TNP) consists of cooking of the grain in abundant water (2–3 l of water per kilogram of maize processed) with 1–3% $Ca(OH)_2$ at temperatures near boiling, for 35–70 min, with a steeping period of 8–16 h. After the steeping, the lime cooking solution (nejayote) is decanted, and the grain is thoroughly washed to leave the grain (nixtamal) ready for milling to produce the masa (maize dough) for making the tortillas. It is well known that TNP enhances the nutritional value of maize proteins by increasing the availability of

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the essential amino acids in the different fractions [5], and leading to the incorporation of calcium ions into the cooked grain [6]. Unfortunately, TNP also leads to losses of some nutrients including lipids, proteins, amino acids, dietary fibre, vitamins and minerals. Due to this fact, the tortilla industry suffers from a compromise in tortilla quality due to low protein levels, as well as deficiencies in lysine and tryptophan. Due to the growing interest in consumption of tortillas in several countries around the world, many studies have been conducted regarding tortilla fortification. In these studies, the chemical score of protein was increased by adding: soybean flour [7, 8], defatted soybean flour [9], sesame and sorghum [10], cottonseed flour [11], germinated corn [12], spent soymilk residue, and lysine and tryptophan incorporation [13, 14]. However, such strategies have proven to be expensive and/or impractical, due to the changes in the physicochemical, textural and sensorial properties of the enriched tortilla.

Over the past four decades, alternative technologies for producing maize flours to prepare tortillas have been proposed, including drum drying [15], micronizing or dry heat treatment [16], microwave and ohmic heating [17, 18], extrusion [19], ecological nixtamalization [20] and power ultrasound [21]. However, nixtamalized products made by these methods are not comparable in quality to those obtained through traditional nixtamalization. In order to eliminate the above-mentioned disadvantage, it has become necessary to find new alternative methods or modifications to TNP. Consequently, the present research was conducted to investigate the physicochemical, quality, compositional, nutritional and viscoamylographic properties of maize tortillas produced by two alternative nixtamalization processes, ultrasonic-bath heating and infrared cooking, and compared to those of tortillas produced by TNP. The alternative technologies were selected in order to explore the effect of other not complex heating systems to suggest alternative methods that have no greater deviation from the traditionally established nixtamalization process for possible commercial applications.

MATERIALS AND METHODS

Maize grain

Regular maize of the commercial hybrid AS-900 (Aspros Comercial, Cortazar, Guanajuato, Mexico) grown and harvested in 2012 at Celaya-Guanajuato, Mexico, with 9.6% moisture content (*MC*), was utilized. This material had a thousand-kernel weight and test weight of 283.40 g ± 3.64 g and 71.59 $kg \cdot hl^{-1}$ ± 1.23 $kg \cdot hl^{-1}$, respectively. The *MC* was determined by forced air oven (Blue M, Blue Island, Illinois, USA) drying at 103 °C for 72 h, with three replicates of 5–10 g each of whole grain, with percentages calculated on a wet-weight basis [22].

Tortilla-making processes

For traditional nixtamalization, three 1 000 g whole maize samples were mixed with 3 l of tap water, and 10 g of $Ca(OH)_2$ were added (JT Bajer, Xalostoc, Estado de Mexico, 99% calcium hydroxide). The maize was gas-fire cooked in a covered aluminium pan for 37 min at 80 °C. For ultrasonic-bath heating and infrared nixtamalization, the maize was cooked using the same maize/tap water input ratio, cooking time and lime content as in TNP.

For ultrasonic-bath heating, a multi-frequency Transsonic TI-H-5 (Elma, Hans Schmidbauer, Singen, Germany) unit was used. The stainless-steel transducer tank was set at a temperature of 80 °C, and the nixtamal was cooked with an ultrasound frequency of 25 kHz using an average power of 100%. The ultrasound frequency of 25 kHz was chosen because cavitation action is much more vigorous at lower frequencies. The power output of the ultrasonic transducer was 550 W.

For infrared-heating, the cooking stage was carried out in a 12 l capacity domestic commercial convection infrared oven (Thane International, model AX-767MH, Zhejiang, China), with an average cooking temperature set at 260 °C. Using this temperature condition, the nixtamal was cooked at approximately 80 °C. The power output of the infrared lamp specified by the manufacturer was 1 300 W, and the operating frequency was 60 Hz.

After nixtamalization, the cooked grain was steeped in a closed plastic container for 18 h at room temperature (24 °C) and the nejayote was removed. The cooked maize was washed with 3 l of tap water to remove lime excess and pericarp tissue. Finally, the nixtamal was stone-ground (FUMASA, Model MN-400, Puebla, Mexico) to provide a masa with *MC* of about 54%.

Tortilla preparation

Masa was compressed into thin disks of approximately 12.5 cm diameter, 1.2 mm thickness and 28 g weight, using a commercial tortilla roll machine (Model TM-G, Casa Gonzalez, Monterrey Nuevo Leon, Mexico). Tortillas were baked for 17 s on one side (first side), 55 s on the other side, and again 17 s on the first side on a griddle at 270 °C. The temperature was measured with a non-contact portable infrared thermometer Fluke-572 (Fluke, Melrose, Massachusetts, USA). Finally, masa (500 g) and tortillas from each treatment (n = 30) were oven-dried at 40 °C for 48 h, then milled and stored at 4 °C in polyethylene bags for further analysis. Fresh tortillas were also kept for determination of some quality properties.

Physicochemical properties

pH

The pH was determined according to the AOAC method 943.02 [23]. Ten grams of sample were suspended in 100 ml of recently boiled distilled water. The suspension was shaken (25 Hz, 25 °C, 30 min) using an orbital shaker (Cole Parmer Model 21704-10; Vernon Hills, Illinois, USA). After 10 min, the supernatant liquid was decanted and pH was immediately determined using a pH meter, Model PC45 (Conductronic, Puebla, Mexico). pH determinations were performed in triplicate for each independent experiment.

Colour

Tortillas were subjected to surface-colour analysis with a MiniScan XE model 45/0-L colorimeter (Hunter Associates Laboratory, Reston, Virginia, USA). The colorimeter was calibrated with a white porcelain plaque (L = 97.02, a = 0.13, b = 1.77). Readings were made in triplicate at four positions at 90° with respect to each other. Three derived functions, total colour difference (ΔE), chroma (C^*), and hue angle (h), were computed from the L, a, and b readings, as follows:

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (1)$$

$$C^* = \sqrt{\frac{a^2}{b^2}} \quad (2)$$

$$h = \arctan \frac{b}{a} \quad (3)$$

Quality properties

Puffing degree

Tortilla puffing was evaluated subjectively by using scores of 1–3, where: 1 – little or no puffing (0–25%), 2 – medium puffing (25–75%), and 3 – complete puffing (75–100%), as recommended by Cuevas-Martínez et al. [24]. Three tortillas for each independent experiment were evaluated.

Rollability

Rollability was evaluated by rolling a tortilla over a 1 cm diameter tube, quantifying the extent of breakage utilizing a scale of 1–3, where: 1 – tortillas with no breaking; 2 – partial breaking at the center and edges of the tortilla; and 3 – completely flattened tortillas [24]. Tortillas were kept in thermically insulated plastic containers and, within 15 min after preparation, warm tortillas (45 °C) were subjected to rollability test. Three tortillas for each independent experiment were evaluated.

Weight loss of tortilla during cooking

The weight loss (WL) of tortilla was determined by weighing the tortilla before and after cooking, three tortillas for each independent experiment being evaluated. The value was reported as percentage (w/w) computed as:

$$WL = \frac{(W_a - W_b)}{W_a} \times 100 \quad (4)$$

where W_a, W_b is weight of tortilla before and after cooking, respectively.

Compositional analysis

The following analyses were performed in triplicate for maize and tortillas: MC (drying at 105 °C for 24 h); ash (incineration at 550 °C); crude protein (micro-Kjeldahl, N × 6.25); crude fat (defatting in a Soxhlet equipment with hexane); and crude fibre content (acid and alkaline hydrolysis), following AOAC official methods 925.10, 923.03, 960.52, 920.39C, and 962.09E, respectively [23].

Nutritional properties

Lysine

Lysine analysis was performed using the method described by López-Cervantes et al. [25] using high performance liquid chromatography (Alliance HPLC; Waters Associates, Milford, Massachusetts, USA), equipped with a Waters Nova-Pak C18 reverse-phase column (4 μm, 3.9 mm × 150 mm) maintained at 38 °C. Flour samples (50 mg) were hydrolysed at 110 °C with 10 ml of 6 $mol \cdot l^{-1}$ HCl for 24 h. The hydrolysed sample was filtered and the extract diluted 200 times with MilliQ water (EMD Millipore, Billerica, Massachusetts, USA). A 300 μl aliquot of the extract was dried and derivatized with the same amount of 9-fluorenylmethyl-chloroformate (FMOC). Standards as well as sample amounts (20 μl), were injected into HPLC and eluted with a mobile phase of 30 $mmol \cdot l^{-1}$ ammonium phosphate (pH 6.5) in 15 : 85 (v/v) methanol : water; 15 : 85 (v/v) methanol : water; and 90 : 10 (v/v) acetonitrile : water, at a flow rate of 1.2 $ml \cdot min^{-1}$. The gradient program employed was as reported by LÓPEZ-CERVANTES et al. [25]. Lysine was fluorometrically detected and identified using a fluorescence detector (Waters model 2475); the excitation and emission wavelengths were 270 nm and 316 nm, respectively. Analyses were done in triplicate.

Tryptophan

Tryptophan analysis was performed using the colorimetric method described by NURIT et al. [26]. Flour samples were defatted with hexane in a Soxhlet-type continuous extractor for 6 h. After hexane evaporation, 80 mg of powder was digested using 3 ml of 4 $mg \cdot ml^{-1}$ papain solution in 0.165 $mol \cdot l^{-1}$ sodium acetate. The tubes were incubated at 65 °C for 16 h, allowed to cool to room temperature, and centrifuged at 3600 ×*g* for 10 min. Subsequently, 1 ml of the supernatant was carefully transferred to a clean tube, and 3 ml of a colorimetric reagent (0.1 $mol \cdot l^{-1}$ glyoxylic acid in 3.5 $mol \cdot l^{-1}$ H_2SO_4 + 1.8 $mmol \cdot l^{-1}$ $FeCl_3 \cdot 6H_20$ + 15 $mol \cdot l^{-1}$ H_2SO_4) was added. Samples were vortexed and then incubated at 65 °C during 30 min. Samples were allowed to cool to room temperature before reading their absorbance at 560 nm in a Beckman-Coulter DU-530 UV-visible spectrophotometer (Beckman- Coulter, Brea, California, USA). A calibration curve was constructed using standard tryptophan (Sigma, St. Louis, Missouri, USA). Analyses were done in triplicate.

In vitro protein digestibility

In vitro protein digestion (*PD*) was performed using the AOAC method 982.30G [23]. A multi-enzyme cocktail, consisting of a mixture of porcine pancreatic trypsin type IX, porcine intestinal peptidase grade I, bovine pancreatic α-chymotrypsin type II, and bacterial protease (Sigma), was used. Sodium caseinate was used as a control (10 g suspended in 200 ml distilled water and adjusted to pH 8 with NaOH). Flour samples and distilled water were used to prepare 10 ml of an aqueous protein suspension (10 mg N) with pH adjusted to 8.0, while stirring in a water bath at 37 °C during 1 h. The multi-enzyme cocktail was maintained in an ice bath and adjusted to pH 8.0. While stirring, 1 ml of the multi-enzyme solution was added to the protein suspension and 10 min after addition, 1 ml of bacterial protease was added and then the mixture was transferred to 55 °C bath for 9 min. Exactly, 19 min after reaction, vials were transferred back to 37 °C bath. The rapid pH drop was recorded automatically over a 20 min period using a pH meter (Conductronic). Samples were analysed in triplicate. Percentage of *PD* was calculated as follows:

$$PD = 234.84 - 22.56\ (pH\ value) \qquad (5)$$

where 234.84 is the intercept, and 22.56 is the slope in the linear regression equation.

Viscoamylographic properties

Relative viscosity of water suspensions of the ground material was determined in a Rapid Visco Analyzer RVA-4 (Newport Scientific, Sydney, Australia). Tortillas were dried in a vacuum oven at 40 °C during 48 h, then milled and sieved to provide the ground material with a particle size of < 250 μm (60 US mesh, sieve size, 0.251 mm). A sample of 3.5 g adjusted to 14% *MC* was placed in a can for RVA and suspended in 25.5 g distilled water. A plastic stirring paddle was placed in the sample can, which was then fixed into RVA, and the heating cycle was activated through a split copper block. The analyser used a time-temperature program as follows: initiating at 50 °C (1 min), increasing the temperature to 92 °C at a rate of 5.6 $°C \cdot min^{-1}$ (7.5 min), remaining 5 min at that temperature, and later decreasing the temperature to 50 °C at the same rate used during the heating, and remaining at that temperature for 2 min, with a total test time of 23 min. The rotational frequency of the paddle was 14.3 Hz for the first 10 s, then 2.7 Hz for the remainder of analysis. From the pasting curves, the values of viscosity peak and setback (difference between the viscosity at the end and the beginning of the cooling period) were registered. Samples were analysed in triplicate.

Experimental design and statistical analysis

The experiment was conducted as a completely randomized design, the three experimental conditions were carried out with three replicates. Data were assessed by analysis of variance (ANOVA) and means comparisons were performed according to the Dunnett's test using the Statistical Analysis System (SAS Institute, Cary, North Carolina, USA). A significance value of $p = 0.05$ was used to distinguish significant differences between treatments.

RESULTS AND DISCUSSION

Tab. 1 shows the physicochemical, compositional and nutritional properties of the maize grain studied. Results on these properties are quite similar to those reported previously by other researchers [27–29]. On the other hand, significant differences were determined in masa for *MC* and pH, as shown in Tab. 2 among physicochemical

Tab. 1. Physicochemical, compositional and nutritional properties of the maize grain.

	Maize (AS-900)
Physicochemical properties	
Moisture content [%]	9.6 ± 0.1
pH	6.46 ± 0.02
Colour	
Luminosity *L*	64.15 ± 0.03
Total colour difference Δ*E*	37.93 ± 0.04
Chroma *C**	20.70 ± 0.05
Hue angle *h*	82.29 ± 0.13
Proximate composition	
Protein [%]	9.3 ± 0.0
Lipids [%]	6.6 ± 0.0
Ash [%]	1.8 ± 0.1
Crude fibre [%]	2.3 ± 0.0
Saccharides [%]	80 ± 0.1
Nutritional properties	
Lysine [g·kg^{-1}]	33.95 ± 0.27
Tryptophan [g·kg^{-1}]	6.81 ± 0.09
In vitro protein digestibility [%]	75.2 ± 2.0

Mean values of three replicates ± standard error are presented.
Proximate composition is expressed on dry basis. Saccharides were determined by difference. Lysine and tryptophan are expressed per kilogram of proteins.

properties of masa and nejayote produced by the three different alkaline-cooking processes. Masa from traditional nixtamalization had the highest *MC* and pH value, 57.6% and 8.47, respectively (Tab. 2). The lowest pH (7.35) was observed in masa from infrared nixtamalization. Ultrasonic-bath nixtamalization produced nejayote with the highest content of organic solids (3.5%); on the contrary, infrared nixtamalization registered the lowest value in this parameter (1.8%). In regard to this respect, Janve et al. [21] reported that the total solid losses for ultrasound nixtamalization was found to be approximately 6% w/w of dry maize, mainly attributed to cavitation effects of the power ultrasound, which caused more leaching of soluble compounds due to the sono-induced endosperm and pericarp separation. Campechano-Carrera et al [20] reported 3.2% organic matter content in nejayote from traditional nixtamalization and values up to 1.4% from ecological variants using calcium salts. Moreover, Gutiérez-Uribe et al. [30] reported contents of organic solids from 2.5% to 7.9% in nejayote obtained by traditional lime-cooking of different types of maize kernels. Our data on total solids for nejayote from traditional nixtamalization were in close agreement with the values found by those researchers. However, lower values of organic solids were registered by us in nejayote from ultrasonic-bath nixtamalization. The extremely wide range of the data may be a consequence of the high variability between the process parameters used, considering that dry matter losses are primarily influenced by several processing parameters, including the maize genotype, endosperm hardness, cooking and steeping times, and type of heating.

With infrared nixtamalization, 41% and 47% less of the total solids were lost as compared to the traditional and ultrasonic-bath nixtamalization, respectively. The reduced solids found in infrared nejayote is a great advantage, since nejayote is one of the most difficult to treat waste waters due to the high content of organic soluble and insoluble solids [31]. Significant differences were also found in pH values of nejayote, where infrared nixtamalization produced nejayote with the highest pH (11.45). The lowest pH (10.96), was registered in nejayote from traditional nixtamalization (Tab. 2). Maya-Cortés et al. [32] reported a pH value of 12 in nejayote from traditional nixtamalization, while other authors reported pH values of nejayote ranging from 10.5 to 11.2 [33, 34].

Tab. 2. Physicochemical properties of maize dough (masa) and steep liquor (nejayote) produced by different alkaline-heating processes.

		Alkaline-heating process		
		Traditional	Ultrasonic-bath	Infrared
Maize dough (masa)	Moisture content [%]	57.6 ± 0.1 ^{a}	54.7 ± 0.1 ^{b}	55.5 ± 0.1 ^{c}
	pH	8.47 ± 0.02 ^{a}	7.92 ± 0.01 ^{b}	7.35 ± 0.03 ^{c}
Steep liquor (nejayote)	Organic solids [%]	3.1 ± 0.0 ^{a}	3.5 ± 0.0 ^{b}	1.8 ± 0.0 ^{c}
	pH	10.96 ± 0.02 ^{a}	11.27 ± 0.01 ^{b}	11.45 ± 0.01 ^{c}

Mean values of three replicates ± standard error are presented. Means with the same letter in the same row are not significantly different (Dunnett's test, $p > 0.05$).

Tab. 3. Physicochemical and quality properties of tortillas produced by different alkaline-heating processes.

	Alkaline-heating process		
	Traditional	Ultrasonic-bath	Infrared
Physicochemical properties			
Moisture content [%]	49.2 ± 0.1 [a]	45.9 ± 0.5 [b]	45.0 ± 0.1 [b]
pH	8.49 ± 0.03 [a]	7.95 ± 0.05 [b]	7.39 ± 0.04 [c]
Colour			
Luminosity *L*	64.21 ± 0.92 [a]	64.40 ± 0.58 [a]	65.02 ± 0.37 [a]
Total colour difference Δ*E*	37.96 ± 0.55 [a]	37.66 ± 0.18 [a]	38.75 ± 0.26 [a]
Chroma *C**	20.87 ± 0.14 [a]	22.23 ± 0.24 [b]	23.63 ± 0.19 [c]
Hue angle *h*	86.67 ± 0.73 [a]	86.41 ± 0.19 [a]	86.33 ± 0.41 [a]
Quality properties			
Puffing	3 [a]	3 [a]	3 [a]
Rollability	1 [a]	1 [a]	1 [a]
Loss of weight [%]	21.8 ± 0.0 [a]	20.8 ± 0.4 [a]	17.5 ± 0.2 [b]

Mean values of three replicates ± standard error are presented. Means with the same letter in the same row are not significantly different (Dunnett's test, $p > 0.05$).

Physicochemical properties of tortillas

Some physicochemical properties of tortillas are listed in Tab. 3. Regarding *MC*, significant differences were not observed between ultrasonic-bath and infrared tortillas, the average *MC* being 45.5%. Tortillas from traditional nixtamalization had the highest *MC* value (49.2%). Méndez-Albores et al. [35] reported *MC* from 41.9% to 42.2% for tortillas made using TNP from maize stored at high moisture. Also, Méndez-Albores et al. [29] reported *MC* of 53.7% in tortillas produced from the commercial instant maize flour MASECA® (Grupo MASECA, Nuevo Leon, Mexico). Those *MC* values in tortillas are in close agreement with these results. The pH values of tortillas showed significant differences, even when nixtamalization was performed with the same lime content (1%, w/w). Tortillas produced with traditional, ultrasonic-bath and infrared nixtamalization presented average pH values of 8.49, 7.95, and 7.39, respectively (Tab. 3). Martínez-Flores et al. [36] produced tortillas from extruded fresh masa with pH values from 6.68 to 8.45, using 0.25% (w/w) calcium hydroxide. In nixtamalized products, lime content represents an important factor in colour, odour, flavour, shelf life and texture characteristics. When the lime content is not sufficient to give the characteristic alkaline flavour, the tortillas are rejected by consumers. Likewise, if this compound is in excess, tortillas become astringent and are also rejected.

Regarding tortilla surface colour analysis, significant differences were not detected for luminosity (*L*), total colour difference (Δ*E*) and hue angle (*h*). However, slightly higher values on *L* and Δ*E* were registered in tortillas produced with infrared nixtamalization (Tab. 3). Méndez-Albores et al. [29] reported *L* and Δ*E* values of 65.03 and 38.22 for tortillas produced by microwave nixtamalization using 0.5% (w/w) lime, respectively. Waliszewski et al. [14] reported hue angle values of 90.35 in tortillas produced with fresh nixtamalized corn flour. Moreover, chroma values (*C**) significantly differed among treatments, thus tortillas from traditional, ultrasonic-bath and infrared nixtamalization presented values of 20.87, 22.23 and 23.63, respectively (Tab. 3). In this research, the amount of lime retained during nixtamalization significantly affected chroma values of tortillas, thus higher chroma values, as in the case of tortillas prepared by infrared heating, indicated that colour was more "pure" in these samples, since chroma represents colour "purity". In general, as the alkali content decreased in tortillas, higher chroma values were observed (Tab. 3). Waliszewski et al. [14] reported a chroma value of 20.32 for tortillas made from nixtamalized corn flour. These results on colour are in close agreement with those obtained in this research for traditional tortillas. In general, changes in the colour of tortillas are directly attributed to the amount of lime retained during the cooking of the nixtamal. Lime content affects the tortilla colour even when tortillas are produced from white maize grains, and the colour intensity is closely related to carotenoid pigments, flavonoids and pH. However, the development of colour during the alkaline-cooking process is more complex, considering that the lime reacts with the different pigments found in the grain and interferes with browning reactions such as caramelization and Maillard reactions [37].

Quality properties of tortillas

Tab. 3 shows the quality properties of tortillas. All tortillas evaluated had similar puffing, presenting a value of 3, which indicates a complete puffing (75–100%). A good puffing is obtained when two layers are formed in the tortilla. These layers, produced during the cooking process, are impermeable, retaining the steam that gives rise to the puffing during heating. Also, all tortillas evaluated presented a good rollability (with a value close to 1), defined as no breaking. Therefore, tortillas from all treatments were also considered within the acceptable margins of quality, presenting a soft manual texture and could be rolled without breaking. The values of weight loss during tortilla baking are also presented in Tab. 3. Tortillas from traditional and ultrasonic-bath nixtamalization had no significant differences in loss of weight, the average value being 21.3%. On the contrary, a lower value (17.5%) was registered in tortillas from infrared nixtamalization. This phenomenon was interesting, due to the fact that tortillas produced with infrared nixtamalization retained slightly more *MC* during cooking than traditional and tortillas prepared by ultrasonic-bath cooking. Figueroa-Cárdenas et al. [5] reported loss of weight values around 23% for tortillas prepared from nixtamal, and Arámbula-Villa et al. [19] reported values of up to 23.5% loss of weight for tortillas from extruded instant maize flour supplemented with various types of lipids. These results are consistent with the values found in our research. The lowest loss of weight means the better tortilla quality, due to the fact that *MC* plays an important role on tortilla yield and texture.

Compositional properties of tortillas

Tab. 4 shows the proximate composition of tortillas. In general, protein content was slightly reduced after nixtamalization. Protein content in raw maize was 9.3% dry basis (Tab. 1), and when nixtamalized, protein was reduced to 8.8%, 8.6%, and 8.7% dry basis for traditional, ultrasonic-bath and infrared nixtamalization, respectively (Tab. 4). These reductions (5.7%, 7.8%, and 6.9%) are consistent with previous reports, which indicate that protein is lost during tortilla elaboration, probably due to solubilization of some protein fractions [38]. On the contrary, lipid content was higher in tortillas prepared by infrared nixtamalization, presenting an average content of 4.3% dry basis, which means that infrared nixtamalization degraded 34.2% of the initial lipid content of the grain. Tortillas prepared by traditional and ultrasonic-bath nixtamalization did not significantly differ in the lipid content, showing an average reduction of 48.9%. The rest of the components (ash, crude fibre and saccharides) presented no significant differences among treatments (Tab. 4).

Tab. 4. Proximate composition and nutritional properties of tortillas produced by different alkaline-heating processes.

	Alkaline-heating process		
	Traditional	Ultrasonic-bath	Infrared
Proximate composition			
Protein [%]	8.8 ± 0.1 a	8.6 ± 0.0 b	8.7 ± 0.0 a
Lipids [%]	3.5 ± 0.2 a	3.3 ± 0.1 a	4.3 ± 0.3 b
Ash [%]	1.7 ± 0.2 a	1.7 ± 0.3 a	1.8 ± 0.2 a
Crude fibre [%]	1.8 ± 0.1 a	1.8 ± 0.2 a	1.9 ± 0.4 a
Saccharides [%]	84.2 ± 0.1 a	84.6 ± 0.0 a	83.3 ± 0.2 a
Nutritional properties			
Lysine [$g \cdot kg^{-1}$]	25.52 ± 0.43 a	25.89 ± 1.39 a	26.57 ± 0.65 a
Tryptophan [$g \cdot kg^{-1}$]	2.02 ± 0.05 a	2.46 ± 0.04 b	3.48 ± 0.06 c
In vitro protein digestibility [%]	84.5 ± 0.1 a	84.2 ± 0.1 a	84.6 ± 0.1 a

Mean values of three replicates ± standard error are presented. Means with the same letter in the same row are not significantly different (Dunnett's test, $p > 0.05$).
Proximate composition is expressed on dry basis. Saccharides were determined by difference.

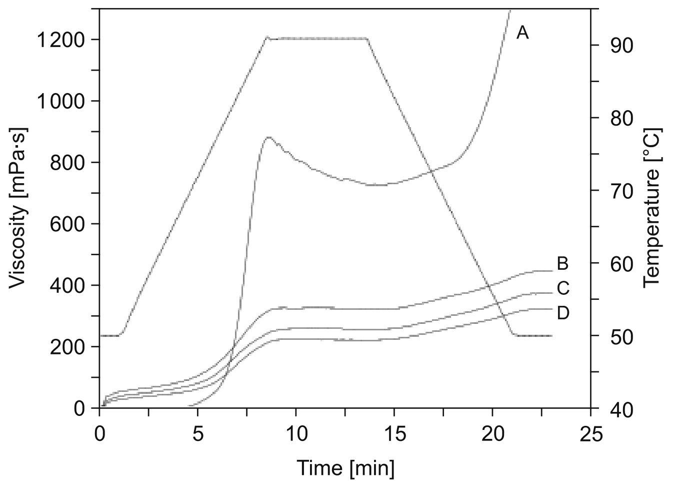

Fig. 1. Viscoamylographic profiles of maize and tortillas produced by ultrasonic, infrared and traditional nixtamalization processes.

A – maize, B – ultrasonic nixtamalization, C - infrared nixtamalization, D - traditional nixtamalization.

Nutritional properties of tortillas

With respect to nutritional properties, there was no significant difference in lysine content. However, lysine was reduced by 23.4% in tortillas. Tortillas presented an average lysine content of 25.99 g·kg^{-1} protein (Tab. 4). Also, tryptophan was degraded to some extent during nixtamalization. The tryptophan content in tortillas prepared by traditional, ultrasonic-bath and infrared nixtamalization were 2.02 g·kg^{-1}, 2.46 g·kg^{-1}, and 3.48 g·kg^{-1} protein, respectively. These values correspond to amino acid degradation of about 70.3%, 63.9% and 48.9%, respectively. CUEVAS-MARTÍNEZ et al. [24] reported reductions of 9.6% and 52.6% in the total lysine and tryptophan contents, respectively, during traditional nixtamalization using 1.5% lime. Those differences in amino acid reduction could be directly attributed to the lime retained during nixtamalization. Tryptophan, an amino acid highly sensitive to the thermal-alkaline treatment, is considered the first limiting amino acid in tortillas, thus tortillas produced by traditional, ultrasonic-bath and infrared nixtamalization covered 21.0%, 25.6% and 36.3%, respectively, of the FAO/WHO requirements [39]. The second limiting amino acid is lysine, covering 47.8% in tortillas produced by the three different nixtamalization procedures. Tortillas from infrared nixtamalization process contained 72% and 41% more tryptophan in comparison with traditional and ultrasonic-bath tortillas, respectively. Tab. 1 and Tab. 4 show the in vitro protein digestibility values of raw maize and tortillas, respectively. As expected, tortillas had higher protein digestibility average value (84.4%) in comparison with maize grain (75.2%). In this research, the parameter increased when maize was processed into tortillas, and no significant differences were determined for tortillas elaborated by the three different nixtamalization processes (Tab. 4). In this context, MÉNDEZ-ALBORES et al. [29] reported protein digestibility values of 76.2% and 84.1% for maize and tortillas, respectively, produced by microwave nixtamalization. Those results are in accordance with the ones reported in this research.

Viscoamylographic properties of maize and tortillas

Fig. 1 shows the typical viscoamylographic profiles of maize and tortillas elaborated by the different methods. Raw maize (profile A) presented the highest peak of viscosity (884 mPa·s) and setback (694 mPa·s). On the contrary, nixtamalization caused a notable decrease in viscosity peak and setback. However, the differences were not significantly different for the viscosity peak. Tortillas from ultrasonic-bath, infrared, and traditional nixtamalization presented viscosity peaks of 241 mPa·s, 298 mPa·s, and 258 mPa·s, respectively (profiles B, C, and D). Regarding setback, there were no significant differences in tortillas from ultrasonic-bath and traditional nixtamalization (profiles B and D), the average value was 109 mPa·s. However, tortillas from infrared nixtamalization (profile C) presented the lowest setback value (88 mPa·s). When cooled, pastes will form a viscoelastic gel, the molecular re-association that occurs during the cooling and storage of gelatinized starch molecules to form an ordered structure are defined as starch setback. Starch setback is influenced by the fine structure of amylopectin and the amylose/amylopectin ratio [40]. During tortilla production, there is enough time and *MC* to gelatinize starch granules, to disperse some of the starch, and to cause much of the amylose become insoluble (retrograde) by the time the product has cooled to room temperature. Setback of amylopectin is believed to involve association of its outer branches and requires a longer time and a lower temperature than amylose to retrograde. Thus, setback of amylopectin occurs with time after the product has cooled [41]. It is most likely that extreme pH values are also a contributing factor to starch degradation, resulting in lower viscosity and higher setback, as in the case of tortillas from traditional and ultrasonic nixtamalization. In this work, it appears that viscosity peak and particularly setback in tortillas prepared by infrared nixtamalization were influenced by the amount of lime retained during the cooking of the nixtamal.

Infrared heating has recently been adopted for use in certain food processing applications, because of its superiority in terms of costs and the quality of the products as compared with conventional heating [42], due to the following physical phenomena: a) the wavelengths of the infrared light interact with foods by reflection, absorption, transmission and scattering, b) the dissipation of radiative energy as heat results in particular surface temperature and penetration depth in the treated food depending on its composition, and c) water and organic compounds such as proteins, lipids and starch (the main components of foodstuffs) absorb the infrared energy. All the above produces a uniform heating of foods, resulting in products with highly acceptable sensory and quality characteristics. In this research, infrared nixtamalization process produced tortillas with improved physicochemical, compositional, nutritional and pasting properties.

CONCLUSIONS

The use of infrared heating during alkaline-cooking improved the physicochemical, quality, compositional and nutritional properties of maize tortillas. Due to the low solids content, the nejayote from infrared nixtamalization could be less harmful to the environment, and also the cost of effluent processing could be reduced. Consequently, as an alternative for solving the problem of low protein quality of cereal-based foods caused by the high starch content of cereals, infrared nixtamalization is recommended, without the need for severe modifications to the processing conditions or equipment during tortilla elaboration. A carefully designed process in which maize is properly exposed to the infrared radiation could provide utilization on industrial scale, without the size restriction usually imposed by the domestic infrared heating systems. Moreover, our results reveal that infrared nixtamalization has a potential to be practical and useful in tortilla-producing factories. However, further experimental conditions such as water/maize input ratio, lime content and cooking time need to be tested to determine their effects on tortilla quality. Further research on use of infrared cooking during nixtamalization is encouraged to determine its effect on the commercial and economical viability of this environmentally friendly tortilla-making process.

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