Chapter 7

Physicochemical and Rheological Changes of Starch in Nixtamalization Processes: Extrusion as an Alternative to Produce Corn Flour

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Abstract

Corn tortilla is a food consumed mainly in México and Central America. It provides 50% of total calories ingestion and is a good source of fiber. Tortilla is produced by the nixtamalization process using corn, water and lime. It has been produced by alternative processes as extrusion, reducing cooking liquor, and increasing dietary fiber. The aim of this book chapter is to describe the changes in corn starch by different nixtamalization processes, also are presented the advantages and disadvantages of both processes, encouraging some aspects of producing corn flour by extrusion. The extrusion is a technology that is dependent of process variables and is reflected on quality of end product. Several factors are involved, as feed moisture and temperature, and they have a direct impact on corn starch physicochemical, textural, and rheological properties.

Keywords: starch, nixtamalization, extrusion, corn flour, tortilla

1. Introduction

In México, the main use of maize is the transformation to nixtamal (cooked corn) then into masa (corn dough), tortilla (main product), tamal, or snacks [1, 2]. Tortilla has been considered a good source of fiber and calcium [3] and is staple food in this country.

There are several nixtamalization processes to make those products. The most common is the traditional nixtamalization process (TNP), an ancient process where corn is cooked with water and lime, steeped in alkaline liquor, and washed to remove cooking water. Clean and cooked corn is named nixtamal, which is ground to produce corn masa, then tortilla [4]. Fresh masa is produced in small establishments and also at strict and highly efficient facilities [5]. Fresh corn masa is also dried and grounded to produce corn flour [6]. On the other hand, nixtamalized corn flour (NCF) is produced at industrial scale reducing water, lime, and steeping time, producing nixtamal, which is dried and exposed to successive stages of milling. Fine particle size in the flour is required, getting an easily hydrated product [7].

In both processes, the discharge of cooking liquor (named nejayote with alkaline pH) has an ecological impact [8]. Consequently, economic and commercial implications are involved because high concentrations of soluble solids are discharged in the effluents (2–11%) [9].

Extrusion is a continuous process in which raw matter is transformed in dough because of a combination of shear, feed moisture, and temperature [10]. It has been reported that extrusion cooking increases nutritional content, hygiene, physicochemical and sensorial characteristics of end product, inactivate anti-nutritional agents, and enzymes from raw matter used to elaborate extruded products [11]. Feed moisture content, particle size distribution (PSD), screw configuration, speed, die size, and heat input are important in the quality of end product. Using correctly all these factors, an accelerated process of gelatinization and fragmentation in starch granule can be prevented [12]. Extrusion normally increases the generation of resistant starch [13], and several times melting and fragmentation reactions are initiated [14]. The feed moisture in extrusion is low, water consumption diminishes, and production of alkaline effluent is absent [8].

Corn masa texture is an important factor to consider when tortilla is produced [15]. Tortilla production depends on changes in corn starch of the nixtamalization process, since raw corn is processed through several stages until production of tortilla is done [16, 17]. On each step of the process, changes in starch are in different degree (less or more damage). Good quality of tortilla and others nixtamalized products is synonym of an adequate cooking. Quality is reflected as good cohesiveness and adhesiveness in masa, which means a good performance in the forming rollers. A good process control is performed when the tortilla is formed adequately without being so sticky and gets stuck in the forming rollers. Undercooked masa has poor adhesiveness and causes troubles in the forming rollers [18]. The aim of this review is to describe physicochemical and rheological changes in starch during the traditional nixtamalization process and to compare to those occurring during nixtamalization using the extrusion process. The advances and benefits of producing instant corn flour using the extrusion are also described.

2. Starch

2.1. General characteristics

Starch is found in seeds, roots and tubers, stems, leaves, fruits and even pollen, being organized as discrete particles named granules [19]. Starch granule is insoluble in cold water and

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is present as spheres, ellipsoids, circles, and other irregular shapes. Dimensions of starch granule range from 0.1 to 200 μm [20], and the solubility of starch is increased when warm water is used. Starch is a complex carbohydrate composed of 20–25% amylose and 75–80% amylopectin [21], being the main component of maize kernel.

Amylose is almost linear glucose molecule linked by α-1, 4 D-glucopyranosil linkages; with a molecular weight (MW) of 105 × 10^6 g/mol [22]. Amylopectin integrates anhydroglucose units in a highly structured architecture made of short α-1,4 glucan chains (95%) and α-1,6 linkages (5%) with a MW of 107 × 10^8 g/mol. Amylopectin defines most of the chemical and physical properties of starch from different sources [23]. Starch properties have been attributed to differences in amylopectin structure. These properties include granule swelling (onset of viscosity), peak viscosity, peak temperature, shear thinning during pasting, and gel firmness during storage [24]. They are related with the quality of end product.

2.2. Functional properties of starch

Functionality is concerned with rheological and structuring properties obtained after cooking. Functional properties of starch are associated with molecular level effects (gelatinization temperature, solubilized starch, and retrogradation) and granule level behavior (swelling, solubility index, and rheology of swollen granules) [20, 25]. The functionality of starch granule changes when it is heated in presence of water. Gelatinization changes are manifested as a loss in crystallinity, granular swelling, and increase in solubility [25, 26].

The crystallinity of starch is attributed to linear short chains presented in the amylopectin molecules. It is represented as a three-dimensional crystalline structure shown by X-ray diffraction (X-RD) patterns [23]. Native starch granules have a crystallinity level ranging from 15 to 45% [20] present in an amorphous state and showing the characteristic patterns of cereals (type A) [27]. When the gelatinization process begins in corn starch, which takes place between 70 and 75°C, the crystalline and organized structure of starch is transformed into an amorph state [20], and crystallinity is lost [28].

The leaching of amylose in starch granule is provoked by several factors. Some of the most representative ones are an increase in temperature, presence of other solutes, type and concentration of the starch, and the agitation force applied during heating [27, 29]. Associated with these changes, the retrogradation begins as a kind of internal restructuring in starch, creating a more compact and solid molecule [30, 31]. Retrogradation is dependent on macromolecular structure (chain configuration, ramifications, and distribution of molecular weight) and the botanical source [32].

Starch granules are physically and chemically inert and are not very digestible in the human body. To change them into functional products, they are heated in excess of water and eventually pass from a semicrystalline and relatively indigestible form to an easily digestible amorphous form [30]. As the structure begins to weaken, the granules soak water and swell. Since not all the granules are gelatinized simultaneously, different degrees of swelling and structural disorganization may exist. This process is named annealing and takes place during soaking for a certain period of time at sub gelatinization temperatures, whereby the starch undergoes reorganization in a more ordered structure [31].

3. Nixtamalization processes

3.1. Traditional nixtamalization process (TNP)

The nixtamalization process is performed actually in many countries, especially in México and Central America [4]. The emerging tortilla industry in the United States has the fastest growing segment of the baking industry in the U.S. market, estimating that Americans in year 2000 consumed 85 million tortillas according to Tortilla Industry Association (TIA) [32].

Functional parameters evaluated in nixtamalization process give us an idea of changes taking place in main components of starch, responsible for rheological and textural properties in nixtamalized corn products [33, 34]. Corn starch crystallinity in the nixtamalization process evaluated with X-RD technique usually presents similar defined peaks that correspond to the interplanar spacing values "d" of 5.86, 5.19, 4.90, 4.46, and 3.87Å [16, 33]. During the TNP, the maize loses part of the typical crystalline structure denoting the formation of amylose-lipid complexes [35]. Studies of changes in crystallinity patterns of corn starch using X-ray diffraction caused by the nixtamalization process have been cited in the literature [16, 36–38]. Other investigators [16, 33, 39] have reported loss of Maltese cross of starch during the nixtamalization process of tortilla. Loss of birefringence indicates a loss of molecular order and general molecular reorganization within starch granules [38].

The starch granule swelling begins with the application of heat, changing its structure. Water is introduced within the granule, and H-bonds between water molecules and polar residues of glucose units are transformed [40]. The high amount of polar groups accelerates the water absorption, and the starch granule collapses. After cooking, linkage of amylose and amilopectin happens and then aggregates outside of the internal structure and forms a gel [16, 22].

Structural damage in aleurone layer and some pericarp *strata* of corn were observed using scanning electronic microscopy (SEM) during alkaline cooking to produce nixtamal [40]. Gómez et al. [39] evaluated the microstructural changes of starch during all the stages of the nixtamalization process, and they concluded that the greatest damage in starch was produced during baking of tortilla because of the use of high temperatures (190°C) and also when tortilla chips were produced in the deep frying process.

The thermal characterization is important to define the cooking variables of maize and its products. The nixtamalization process requires maize with low temperature and enthalpy of gelatinization for tortilla production [41]. These values for maize starch are between 67 and 69°C for temperature and 8–16 J/g of starch for enthalpy [42]. Other gelatinization temperature ranges of nixtamalized processed products have been monitored between 70 and 80°C [33, 43], defining their structural and textural characteristics [42]. An extended cooking time and steeping involve more gelatinized starch and lower enthalpy values [5] increasing the gelatinization temperature and producing a more reorganized starch molecule. This parameter also involves a higher degree of crystallinity retrogradation, shortening, and syneresis (water is squeezed out of the granule) of overcooked starch [39]. All these changes are related with corn masa yield [44].

3.1.1. Stages in TNP

3.1.1.1. Cooking and steeping

Cooking of corn is used to hydrate corn kernel, tender the pericarp, denaturalize proteins, and develop partial gelatinization of starch because of absorption of lime in germ [38]. Grains swell because of the combined effect of starch gelatinization, partial degradation of endosperm structure, solubilization of cellular wall, and partial solubilization of proteic matrix [27]. The peripheral and external endosperm also suffers small modifications because of the hardness of nixtamal grain [33]. Optimal cooking of masa is usually evaluated with the measurement of textural parameters such as plasticity, cohesivity, and chewiness [43]. Steeping promotes moisture diffusion inside the grain and produces nixtamal (cooked corn) that is homogeneously hydrated [44]. In the steeping period, swelling and solubility increase, nixtamalized corn grinding results in increased gelatinization and releasing of swollen granules [45]. In this period, the water absorption increases during the early hours because of pericarp removal (90%), allowing rapid diffusion of calcium in starch in the first 8 hours [46]. Cooking temperature, agitation, and average alkali concentration directly affect water uptake and calcium produced by interaction of alkaline solution with components in the corn kernel [47]. Several nutrients and antioxidants are lost, especially those present in yellow corn. It is recommended to select grains with soft endosperm to promote a more efficient action of calcium when interacts with starch pericarp [47, 48].

3.1.1.2. Washing

When nixtamal is washed, excess lime is removed and pH values are diminished, increasing loss of dry matter because of pericarp removal and color improvement observed in products. Some pentosane gums of corn are retained and are useful to maintain flexibility and smoothness in masa and tortillas [49]. Dry matter losses in the nixtamalization process, especially in alkaline cooking, steeping, and corn grain wash are between 5 and 14% (w/w) [50, 51]. Nejayote (cooking liquor) contains pericarp and soluble proteins, which are discharged every time when a batch is completed [52]. Soft endosperm, damaged grain, usage of high boiling temperatures, and excess of lime contribute to increase economic losses [43].

3.1.1.3. Grinding

Washed nixtamal is grounded in a stone mill to produce dough (masa) composed of different kinds of particles, including fragments of germ, pericarp, and endosperm, and other compounds such as entire starch granules, proteins, hydrated fibers, and fat, with 50–60% of humidity [45]. Amylopectin is solubilized as part of the mechanical fragmentation of corn kernel in stone milling [39]. The final masa particle size is affected by the grinding process. Masa particle size used for tortilla must be fine and coarse for snacks and corn chips, which is determined subjectively [53].

3.1.1.4. Mixing and masa formation

Mixing time and masa consistency are critical for a good machinability in tortilla disc-forming machine. During this step, the rheological and textural properties of masa are enhanced, acquiring the final quality that is required in the product [54]. This step includes calculation of dimensions and weight of final product. Soluble starch may increase because of the stone milling, affecting viscosity of starch and diminishing during masa processing [39]. During forming, the masa is rolled into a sheet, which is cut by a rotating cutter positioned underneath the rolls [2].

3.1.1.5. Tortilla baking

This step includes cooking and partial drying of masa, giving a light toast appearance to disc masa and developing final texture of the product. When masa is transformed into tortilla [39], crystallinity disappears or decreases to a higher extent than in the preceding processing steps [16].Temperature, steeping time, and lime concentration impact on textural quality of masa and tortilla [15]. Viscosity, cohesiveness, and adhesiveness of the tortillas are improved by alkaline cooking when corn masa is produced [55] and consequently appropriate texture results in good-quality tortilla. An appropriate texture gives adequate adhesivity when rolling machine is forming and cutting the tortilla. If corn is over-cooked, corn masa is sticky and adheres strongly to the rolls. Under-cooked corn produces a little cohesive masa and inadequate handling for tortilla disc formation [53].

3.2. Industrial nixtamalization process (INP) for corn flour production

The process used to produce NCF includes the following steps: reception, selection, cleaning, and storage, cooking and grinding of grain, dehydration, sifting, classification of product and packaging [56]. Dry masa is produced by drying and grinding lime-cooked and grounded masa. To obtain NCF, it is necessary to mill the nixtamal several times, using low-moisture content, and reducing contact time between starch and lime. These conditions in process affect deeply the structure of starch granule, avoiding the release of other components in corn kernel and changing the functionality of NCF [7].

Functionality of NCF is based on physicochemical characteristics, and it is increased after hydration process of corn masa is done [7]. A quality parameter used by masa manufacturers is water absorption content (WAC). Excessive heating is a major cause that damages starch granule, producing losses in its structure and integrity and producing flours with high WAC [36]. This is observed when certain quantity of water is retained by the hydration of NCF, which is related to a bigger economical profit. This behavior is related to the content of starch and protein levels in NCF particles [7].

The NCF presents a high particle size index (PSI), a quality parameter used to compare different types of flours [57]. The PSI is an indirect measurement of mechanical damage occurring in corn grain [58]. The flours are fractioned and reformulated for specific applications (table tortillas and fried products) [44]. The NCFs exhibit a more homogeneous particle size distribution (PSD) than does those for fried products [39]. The NCF milling is severe, and as a direct consequence, the content of damaged starch is increased when low gelatinization enthalpy values are registered. Textural quality in the NCF differs from TNP, and this behavior is governed by the following reasons:

a. A high value in particle size index (PSI) implies lower values of viscosity, hardness, and adhesivity because of a greater content of soluble solids [6, 59].

b. Water absorption in NCF is bigger than values observed in fresh masa, and more hydrogen bonds are present between starch chains and water molecules [39].

c. Retrogradation increases and shelf life shortens. More reorganization reactions occur because of the ratio and concentration of amylose and amylopectin [60].

d. Rapid drying of masa causes gelatinization and reorientation of starch polymers. A modification of the rheological characteristics of masa is observed when the baking of tortillas is performed, and lower rollability values and higher scores of hardness are registered [39].

When dry masa flour from the traditional process was compared against dry nixtamalized corn flour, gelatinization temperatures were similar; although enthalpy of gelatinization was lower in the second one as a consequence of a higher degree of gelatinization in corn starch [34, 36, 61].

3.3. Nixtamalization process by extrusion (NPE) to produce corn flour

Cooking extrusion is a continuous and a relative low-cost process used to modify the functional and digestible characteristics of cereal grains. All parts of corn grain are ground together, conditioned with lime and water (40–65% based on the weight of corn), and the mixture is heated with electric resistors or steam located at the outer side of the extruder [10]. Extrusion cooking is performed at high temperatures (90–120°C), low moisture, and short time, without the generation of contaminant effluents [62]. During the extrusion, changes in starch produce a higher degree of gelatinization as compared to TNP [1].

The main objective of producing extruded nixtamalized corn flours (ENCFs) is to modify the functional properties of starch. This objective is reached, modifying the extrusion parameters, such as temperature, feed moisture, and the speed of the screw [63–65]. In this way, starches with functional properties similar to those of chemically modified (hydroxypropylated and cross-linked) starches can be obtained without chemical modification. On the other hand, the functional properties of the extruded flours will depend on the extrusion conditions [66, 67]. This interaction is an important factor to consider in extruded products during single-screw extrusion [67–69].

Extrusion cooking modifies the starch crystallinity because the thermal treatment is more aggressive, and consequently, the crystalline structure of raw starch granule is partially or completely destroyed [70, 71]. The extruded nixtamalized corn flour can show a similar behavior to traditional process on gelatinization temperature (80°C) in accordance with adequate process variables observed [14, 17, 72]. There is a higher quantity of damaged starch in extruded corn starch as a consequence of the fragmentation caused by intense shear within the extruder [67, 68]. Loss of crystallinity is caused by mechanical disruption of the molecular bonds inside the starch structure, as a result of the extended dehydration [73].

Other process factors are important in extrusion cooking. Screw speed is considered a major factor, as also expansion index and density of extrudates [74]. A rise in pressure within the extruder is observed when the composition of raw matter changes [75]. Gómez-Aldapa et al. [76] observed that composition of raw matter used to make ENCF had a high impact in the production of tortillas.

The extrusion causes important nutritional changes in flours. A high humidity level and low temperature improve the nutritional characteristics of the treated products, while the more severe treatments (low humidity and high temperatures) make them worse. The treatment conditions can influence the generation of Maillard reactions, with consequent deterioration of the nutritional quality of the proteins. Nutritional composition of tortillas made via extrusion is better than those of the traditional process using integral grain. Gómez-Aldapa et al. [76] performed a nutritional comparison between two types of tortillas. They observed that tortillas made with ENCF had a higher content of dietary fiber and lysine than those prepared with nixtamal. They also concluded that pericarp and soluble solids discharged in cooking liquor diminished the nutritional value of tortillas made with fresh masa. The optimization process is used in extrusion to find the best combination of parameters to formulate a product. Milán-Carrillo et al. [77] established a set of parameters to produce tortillas with optimal conditions using high quantity of lysine and tryptophan maize. There are other formulations made with whole meal to increase nutritional value of flours [78, 79].

Extrusion changes the nutritional properties of nixtamalized products because of:

a. Promotion of a more rapid transfer of water into molecules.

b. The denaturation of proteins, reducing the lipid oxidation by inactivating the enzymes responsible for it. Lysine and protein content are increased.

c. The complex formation and degradation of thermolabile vitamins and pigments.

d. The increase of the soluble fiber content (expressed as damaged and resistant starch).

e. The inactivation of enzymes (responsible for shortened shelf life in products in extrusion) and diminishing the microbial load [13].

The extruded flours produce changes in the rheological behavior of the starches. The involved modifications are similar to when the pastes are subjected to heating and cooling cycles [80]. However, extrusion causes starch changes more abrupt than traditional cooking methods, damaging a greater amount of starch granules and modifying the cold thickening power of the treated starches [81].

The extrusion has been used to produce corn flour and nixtamalized corn masa [82, 83]. However, this technology has not totally replaced the TNP [83]. González-Vera [72] produced tortillas using ENCF of high protein quality maize. The evaluation of the physicochemical changes of starch granule during the process was done. A harder product was produced, as a consequence of more severe damages in corn starch during the grinding and cooking stages.

The tortilla making process involves rupture of crystalline region of the starch granule and loss of molecular integrity producing a decrease in the intensity of the diffraction patterns due to the thermal treatment [16]. Arámbula-Villa et al. [73] produced tortillas using ENCF enriched with 3% (w/w) of pericarp. They observed that viscosity of ENCF was increased with the addition of maize pericarp. Using other concentrations, the viscosity decreased. The viscosity in ENCF is also increased during the production process with the addition of gums [3, 57] and enzymes [68]. The effect of alkaline cooking and lime concentration (from 0 to 1.0%) had direct impact on the viscosity of corn masa, when a Brabender amylograph was used to measure viscosity [6].

The milling of the extrudates and particle size distribution (PSD) of the flour are important parameters that define the functional properties of ENCF [57]. Changes in starch structure are affected by particle size [14]. Hasjim et al. [58] observed that the structure of starch in cereal grains is affected during milling, resulting in a great damage to starch granules. This phenomenon is dependent on milling conditions and type of equipment used. The mechanical damage in starch is different when a blade mill or a hammer mill is used in size reduction [17]. Damaged starch is related to small starch particles that hydrate easily when flour is produced. The higher damage in starch indicates the finest particle. A damaged starch has a higher water absorption capacity, which is good in industry, but too much starch damage leads to sticky and highly adhesive masa [84].

A problem of extruded flour is its low water absorption. The water absorption content (WAC) in ENCF is usually low, and corn masa loses water quickly, due to a high dehydration rate and retrogradation effects. Both factors result in harder tortillas [85]. Drying is important to eliminate water excess in the extrudates, and appropriate conditions are needed to avoid damage to starch and corn matter losses [50]. As an immediate consequence of drying process, starch is degraded and short chains are generated, retaining a higher number of water molecules [45]. Excessive heating affects deeply the structure and integrity of starch granule and will form a gelatinized paste with a higher content of dissolved solids [14]. WAC in masa can be improved using whole corn flour and a combination of ingredients [86].

Another characteristic related with the functionality of ENCF is amylose content [87]. Chinnaswamy and Hanna [65] characterized the macromolecular and functional properties of different corn starches. During extrusion cooking under various conditions, they concluded that starches rich in amylopectin (>50%) degrade faster than starches with a major amylose proportion. When the extrudates are produced at higher temperatures, water loss is more pronounced during cooling than those extruded at lower temperature [88]. Finally, Estrada-Girón et al. [37] evaluated the effect of the moisture content and temperature on the XRD, microstructural, pasting, thermal, and rheological properties of nixtamalized masa. They observed a high dependence of moisture content and temperature when physical and rheological properties were evaluated.

4. Texture and rheology of nixtamalized products

Texture is a sensory perception derived from the structure of food related with viscosity and elasticity [89]. Texture of masa is important because tortilla production is performed taking into account the masa consistency and is reflected in the formation of the sheet, favoring its cutting and shaping as round disks [38]. Texture is affected by endosperm texture, type of endosperm, drying process, storage life, and corn kernel variety, having a direct impact in the production of the different types of flours [90].

Textural properties of nixtamalized corn masa are dependent on the degree of gelatinization of the starch. In general, the corn masa obtained is defined as a mixture consisting of amylose and amylopectin mixed with partially gelatinized starch and intact granules, endosperm parts, and lipids [39]. An overcooked masa will be highly adhesive; meanwhile, an undercooked masa will have low cohesivity and bad machinability when tortillas are made [7]. Adhesiveness is a quality parameter in corn masa production evaluated instrumentally as the maximum tensile force during the adhesion process. It is defined as the cohesive rupture between two flat, circular metal plates, and the food sample [15].

The measurement of textural characteristics is evaluated using objective and subjective methods [91]. The objective methods or instrumental measurements use instruments that give numerical results in physical units and are independent of the operator. These tests can be fundamental, empiric, and imitative. The subjective methods evaluate the food quality using the sense of touch and, for this reason, are tough to standardize [91, 92]. The texture profile analysis (TPA) of masa, including parameters such as hardness, springiness, cohesiveness, and gumminess, is done using a texture analyzer [34]. Contreras-Jiménez et al. [1] evaluated ENCF and did not find differences when compared against the NCF. The hardness value range found in ENCF was between 1.01 and 3.15 N against nixtamal masa hardness value observed (1.79 N). ENCF is usually compared against the masa prepared by TNP, using the right formulation to get similar results in texture. A better texture value in nixtamal is attributed to appropriate swelling of the starch granules, the hydrolysis of the pericarp that release gums from the nixtamalized pericarp (hemicellulose) and the presence of saponified lipids (used in a natural way as enhancers of texture) in the germ [93].

There are several rheological methods to measure texture in corn masa and slurries such as back extrusion [89, 94], squeezing flow viscometry, creep test [95], and dynamic rheology [96]. Dynamic rheology has measured efficiently the viscoelastic properties of materials, especially starch [57]. Sahai et al. [34] found a strong relationship between textural attributes of masa obtained from TPA, the particle size, and the composition. Arámbula-Villa et al. [17] evaluated some textural characteristics of tortillas prepared with four types of gums added before and after extrusion and established ideal textural parameters in the tortilla. Corradini and Peleg [97] applied squeezing flow viscometry to measure the rheology of several semiliquid foods. This method has been useful to characterize corn masa, evaluating rheological properties and monitoring their ability to recover original consistency after a shearing is applied [15].

The measurement of viscoelastic characteristics of masa has been applied successfully to describe the behavior of corn starch using a range that implies a small deformation in the test material. There are two concepts useful to understand viscoelasticity. First, the storage modulus (G') is referred to elastic modulus. Lost modulus (G″) is related to the viscous modulus. Vázquez-Carrillo et al. [98] found a great dependence of G' and G″ on frequency. They observed that G' was always higher than G″, which is a characteristic behavior of starch gels. Méndez-Montealvo et al. [42] observed similar behavior when they measured G' and G″ in nixtamalized maize starch at two stages (90 and 25°C) of the starch gelation. Mondragón et al. [5]

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used small amplitude oscillatory rheometry to study the influence of lime and amylose-lipid complexes on the viscoelastic behavior of nixtamalized maize starch gels and observed that G' and G″ showed to be lime dependent. Platt-Lucero et al. [57] studied the viscoelastic behavior of masa obtained from rehydrated extruded corn flour and observed that G'>G″ at any frequency and for any treatment. Quintanar-Guzmán et al. [38] observed a similar behavior when the viscoelastic properties of corn were evaluated under different nixtamalization conditions.

The measurement of physicochemical properties, especially the moisture content is an important issue to consider. The raw tortilla is highly susceptible to moisture loss. The moisture content in fresh masa and tortilla represents around 40–50% of total weight. An excessive loss of water in final product is related to economic losses, which is unacceptable for producers. High moisture content in tortilla is related to a high microbiological charge causing a brief shelf life and an increase in starch retrogradation [33, 99]. As an immediate consequence, a problem very common in tortillas prepared with masa obtained from ENCF is the gradual increase in hardness [7, 36].

Other physical characteristics evaluated in tortilla are weight, diameter, and thickness. These parameters in tortillas produced via extrusion [57] were similar when compared to those of the traditional nixtamalization process [15]. Tortilla texture includes the measurement of hardness and rollability during the first 48 h. ENCF used to make masa, and thereafter, tortillas can be mixed with gums to increase its WAC and tortilla yield [17]. The effect of extrusion conditions continues to be studied. Chaidez-Laguna et al. [100] emphasized the role of protein content in corn tortilla made with ENCF and concluded that mixing time is critical to enhance the consistency of flour and the texture in the tortilla. Reyes-Moreno et al. [101] improved the end quality and nutritional value of product, since it is very promising to use whole corn grain in the nixtamalization via extrusion.

5. Conclusions

Discussion has been focused in a comparison between the characteristics of several nixtamalization processes. Advantages and disadvantages of nixtamalization and extrusion were discussed. Functional properties are different when starch is processed by diverse conditions. Best textural quality is achieved using traditional alkaline cooking, but it has a wide variation in control process; it produces contaminant effluents, takes long time to be performed, and the production at commercial levels is small. Usage of NCF as an alternative nixtamalization process has proved to be an economic and reliable option to make tortillas. Processing of NCF yields a product with a regular textural quality that stale and mold faster. NCF technology also produces contamination as the traditional way does. Extrusion is a continuous process involving low-feed moisture level, an adequate cooking temperature, and a correct lime addition to produce whole corn extrudates, flour, and then tortillas. Extrusion can be applied correctly handling the process variables to offer an alternative to make corn flours and diminishing a more severe damage in corn starch. Extrusion behaves similarly to traditional way and has approximately the same product quality. Extrusion is performed without pollution, is efficient, and increases nutritional value of corn when adequate raw matter is chosen. There are researchers that support the use of extrusion as an alternative to produce tortilla, and it has been a necessity detected in food industry.

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Nomenclature

NCF	nixtamalized corn flour
MW	molecular weight
TIA	Tortilla Industry Association
TNP	traditional nixtamalization process
INP	industrial nixtamalization process
NPE	nixtamalization process by extrusion
“d”	interplanar spacing
ENCF	extruded nixtamalized corn flour
WAC	water absorption content
PSI	particle size index
PSD	particle size distribution
TPA	texture profile analysis
G'	storage modulus
G″	lost modulus

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References

[1] Contreras-Jiménez B, Morales-Sánchez E, Reyes-Vega ML, Gaytán-Martínez M. Functional properties of extruded corn Flour obtained at low temperature. CytA-Journal of Food. 2014;**12**:263-270

[2] Serna-Saldivar, SO. Química, almacenamiento e industrialización de los cereales. SA México, DF: AGT Editor; 1996. pp. 408-420

[3] Serna-Saldivar, SO, Gómez, MH, Rooney, LW. Technology, chemistry, and nutritional value of alkaline-cooked corn products. Advances in Cereal Science and Technology. 1990;**10**:243-306

[4] Gaytán-Martínez M, Figueroa-Cárdenas JD, Morales-Sánchez E, Vázquez-Landaverde PA, Martínez-Flores HE. Physicochemical properties of masa and corn tortilla made by ohmic heating. African Journal of Biotechnology. 2011;**10**:16028-16036

[5] Mondragón, M, Bello-Pérez, LA, Agama-Acevedo, E, Betancourt-Ancona, D, Peña JL. Effect of cooking time, steeping and lime concentration on starch gelatinization of corn during nixtamalization. Starch-Stärke. 2004;**56**:248-253

[6] Bryant CM, and Hamaker BR. Effect of lime on gelatinization of corn flour and starch. Cereal Chemistry. 1997;**74**:171-175

[7] Bello-Pérez, LA, Osorio-Díaz, P, Agama-Acevedo, E, Núñez-Santiago, C, Paredes-López, O. Chemical, physicochemical and rheological properties of masas and nixtamalized corn flour. Agrociencia. 2002;**36**:319-328

[8] Gutiérrez-Uribe JA, Rojas-García C, García-Lara S, Serna-Saldivar SO. Phytochemical analysis of wastewater (nejayote) obtained after lime-cooking of different types of maize kernels processed into masa for tortillas. Journal of Cereal Science. 2010;**52**:410-416

[9] Bressani R, Paz y Paz R, Scrimshaw NS. Corn nutrient losses, chemical changes in corn during preparation of tortillas. Agricultural and Food Chemistry. 1958;**6**:770-774

[10] Harper JM Extrusion of foods. Volume I. CRC Press Inc. 2000 Corporate Blvd, N.W., Boca Raton, FL USA; 1981; 212 p.

[11] Zhu S, Riaz MN, Lusas EW. Effect of different extrusion temperatures and moisture content on lipoxygenase inactivation and protein solubility in soybeans. Journal of Agriculture and Food Chemistry. 1996;**44**:3315-3318

[12] Guy, RCE. Extrusion cooking technologies and applications. 1st ed. CRC Press. N.W., Boca Raton, FL USA; 2001; 200 p.

[13] Rendón-Villalobos R, Bello-Pérez LA, Osorio-Díaz P, Tovar J, Paredes-López O. Effect of storage time on in vitro digestibility and resistant starch content of nixtamal, masa, and tortilla. Cereal Chemistry. 2002;**79**:340-344

[14] Lai LS, Kokini JL. Physicochemical changes and rheological properties of starch during extrusion. (A review). Biotechnology Progress. 1991;**7**:251-266

[15] Ramírez-Wong B, Sweat VE, Torres-Chávez PI, Rooney LW. Development of two instrumental methods for corn masa texture evaluation. Cereal Chemistry. 1993;**70**:286-290

[16] Campus-Baypoli ON, Rosas-Burgos EC, Torres-Chávez PI, Ramírez-Wong B, Serna-Saldivar SO. Physicochemical changes of starch during maize tortilla production. Starch-Stärke. 1999;**51**:173-176

[17] Arámbula-Villa G, Mauricio SRA, Figueroa-Cárdenas JD, González-Hernández J, Ordorica FCA. Corn masa and tortillas from extruded instant corn flour containing hydrocolloids and lime. Journal of Food Science. 1999;**64**:120-124

[18] Ramirez-Wong B, Sweat VE, Torres-Chávez, PI, Rooney LW. Cooking time, grinding, and moisture content effect on fresh corn masa texture. Cereal Chemistry. 1994;**71**:337-343

[19] French D. Organization of starch granules. Starch: Chemistry and Technology. 1984;**2**: 183-247

[20] BeMiller J N, Whistler R L. Starch: Chemistry and Technology. 3rd ed. Academic Press. CA, USA; 2009.

[21] Thompson DB. Strategies for the manufacture of resistant starch. Trends in Food Science and Technology. 2000;**11**:245-253

[22] Kossman J, Lloyd J. Understanding and influencing starch biochemistry. Critical Reviews in Plant Science. 2000;**19**:171-226

[23] Bello-Pérez LA, Rodríguez-Ambriz SL, Sánchez-Rivera MM, Agama-Acevedo E. Starch macromolecule structure. In: Bertolini AC. Starches: Characterization, Properties, and Applications. Boca Raton: Taylor and Francis. 2010. pp. 33-59

[24] Mua JP, Jackson DS. Relationships between functional attributes and molecular structures of amylose and amylopectin fractions from corn starch. Journal of Agricultural and Food Chemistry. 1997;**45**:3848-3854

[25] Donald AM. Understanding starch structure and functionality. In: Eliasson AC. (Ed). Starch in food: structure, function and applications. CRC Press. 2004. Corporate Blvd, N.W., Boca Raton, FL USA; 2000; pp. 158-179.

[26] Biliaderis CG, Zawistowski J. Viscoelastic behavior of aging starch gels: Effects of concentration, temperature, and starch hydrolysates on network properties. Cereal Chemistry. 1990;**67**:240-246

[27] Buléon A, Colonna P, Planchot V, Ball S. Starch granules: Structure and biosynthesis. International Journal of Biology of Macromolecules. 1998;**23**:85-112

[28] Hill RD, Dronzek BL. Scanning electron microscopy studies of wheat, potato and corn starch during gelatinization. Starch-Stärke, 1973;**25**:367-372

[29] Gidley MJ. Starch structure/function relationships: Achievements and challenges. In: Barsby TL, Donald AM, Frazier PJ. Starch: Advances in Structure and Function. The

Proceedings of Starch 2000: Structure and function held on 27-29 March 2000 at Churchill College, Cambridge. pp. 1-4

[30] Tester RF, Debon SJJ. Annealing of starch: A review. International Journal of Biological, Macromolecules. 2000;**27**:1-12

[31] Figueroa-Cárdenas JD, Véles-Medina JJ, Hernández-Landaverde MA, Aragón-Cuevas F, Gaytán-Martínez M, Chávez-Martínez E, Palacios N, Willcox M. Effect of annealing from traditional nixtamalisation process on the microstructural, thermal, and rheological properties of starch and quality of pozole. Journal of Cereal Science. 2013;**58**:457-464

[32] Tortilla Industry Association [Internet]. 2016. Available from: http://tortilla-info.com [Accessed: 20-09-2016]

[33] Gómez MH, McDonough CM, Rooney LW, Waniska RD. Changes in corn and sorghum during nixtamalization and tortilla baking. Journal of Food Science. 1989;**54**:330-336

[34] Sahai D, Mua JP, Surjewan I, Buendía MO, Rowe M, Jackson DS. Alkaline processing (nixtamalisation) of white Mexican corn hybrids for tortilla production: Significance of corn physicochemical characteristics and process conditions 1. Cereal Chemistry. 2001;**78**:116-120

[35] Mariscal-Moreno RM, Figueroa-Cárdenas JD, Santiago-Ramos D, Arámbula-Villa GA, Jiménez-Sandoval S, Rayas-Duarte P, Véles-Medina JJ, Martínez-Flores HE. The effect of different nixtamalization processes on some physicochemical properties, nutritional composition and glycemic index. Journal of Cereal Science. 2015;**65**:140-146

[36] Bello-Pérez LA, Osorio-Díaz P, Agama-Acevedo E, Solorza-Feria J, Toro-Vázquez J, Paredes-López O. Chemical and physicochemical properties of dried wet masa and dry masa flour. Journal of Science Food Agriculture. 2003;**83**:408-412

[37] Estrada-Girón Y, Aguilar J, Morales-del Rio JA, Valencia-Botín AJ, Guerrero-Beltrán JA, Martínez-Preciado AH, Fernández VVA. Effect of moisture content and temperature on the rheological, microstructural and thermal properties of masa (dough) from a hybrid corn (*Zea Mays sp.*) variety. Revista Mexicana de Ingeniería Química. 2014;**13**:429-446

[38] Quintanar-Guzmán A, Flores MEJ, Escobedo RM, Guerrero LC, Feria JS. Changes on the structure, consistency, physicochemical and viscoelastic properties of corn (Zea mays sp.) under different nixtamalisation conditions. Carbohydrate Polymers. 2009;**78**:908-916

[39] Gómez MH, Lee JK, McDonough CM, Waniska RD, Rooney LW. Corn starch changes during tortilla and tortilla chip processing. Cereal Chemistry. 1992;**69**:275-279

[40] Ratnayake WS, Wassinger AB, Jackson DS. Extraction and characterization of starch from alkaline cooked corn masa. Cereal Chemistry. 2007;**84**:415-422

[41] Méndez-Montealvo G, Bello-Pérez LA, Solorza-Feria J, Velázquez-del Valle M, Montiel N, Paredes-López O. Composición química y caracterización calorimétrica de híbridos y variedades de maíz cultivadas en México. Agrociencia. 2005;**39**:267-274

[42] Méndez-Montealvo G, Sánchez-Rivera MM, Paredes-López O, Bello-Pérez LA. Thermal and rheological properties of nixtamalised maize starch. International Journal of Biological Macromolecules. 2006;**40**:59-63

[43] Pflugfelder RL, Rooney LW, Waniska RD. Fractionation and composition of commercial corn masa. Cereal Chemistry. 1988;**65**:262-266

[44] Almeida-Domínguez HD, Domínguez-Cepeda M, Rooney LW. Properties of commercial nixtamalized corn flours. Cereal Foods World. 1996;**41**:624-630

[45] Almeida-Domínguez HD, Suhendro EL, Rooney LW. Corn alkaline cooking properties related to grain characteristics and viscosity (RVA). Journal of Food Science. 1997;**62**: 516-519

[46] Gutiérrez-Uribe JA, Rojas-García C, García-Lara S, Serna-Saldivar SO. Effects of lime-cooking on carotenoids present in masa and tortillas produced from different types of maize. Cereal Chemistry. 2014;**91**:508-512

[47] Ruiz-Gutiérrez MG, Quintero-Ramos A, Meléndez-Pizarro CO, Talamás-Abbud R, Barnard J, Márquez-Meléndez R, Lardizábal-Gutiérrez D. Nixtamalisation in two steps with different calcium salts and the relationship with chemical, texture and thermal properties in masa and tortilla. Journal of Food Process Engineering. 2012;**35**:772-783

[48] Gutiérrez-Cortez E, Rojas A, Cornejo-Villegas MA, Zepeda-Benitez Y, Rodríguez-García ME. Microstructural changes in the maize kernel pericarp during cooking stage in nixtamalisation process. Cereal Science. 2010;**51**:81-88

[49] Carvajal-Millan E, Rascón-Chu A, Márquez-Escalante JA, Micard V, Ponce de León N, Gardea A. Maize bran gum: Extraction, characterization and functional properties. Carbohydrate Polymers. 2007;**69**:280-285

[50] Pflugfelder RL, Rooney LW, Waniska RD. Dry matter losses in commercial corn masa production. Cereal Chemistry. 1988;**65**:127-132

[51] Rooney LW, Suhendro EL. Perspectives on nixtamalisation (alkaline cooking) of maize for tortillas and snacks. Cereal Foods World. 1999;**44**:466-470

[52] Rosentrater KA. A review of corn masa processing residues: Generation, properties, and potential utilization. Waste Manage. 2006;**26**:284-292

[53] Ramírez-Wong B, Sweat VE, Torres-Chávez PI, Rooney LW. Cooking time, grinding, and moisture content effect on fresh corn masa texture. Cereal Chemistry. 1994;**71**:337-343

[54] Bello-Perez LA, Paredes-López, O. Starches of some food crops, changes during processing and their nutraceutical potential. Food Engineering Reviews. 2009;**1**:50-65

[55] Martín-Martínez ES, Jaime-Fonseca MR, Martínez-Bustos F, Martínez-Montes JL. Selective nixtamalisation of fractions of maize grain (*Zea mays L.*) and their use in the preparation of instant tortilla flours analyzed using response surface methodology. Cereal Chemistry. 2003;**80**:13-19

[56] Rooney LW, Suhendro EL. Perspectives on nixtamalisation (alkaline cooking) of maize for tortillas and snacks. Cereal Foods World. 1999;**44**:466-470

[57] Platt-Lucero LC, Ramírez-Wong B, Torres-Chávez PI, López-Cervantes J, Sánchez-Machado, DI, Reyes-Moreno C, Morales-Rosas I. Improving textural characteristics of tortillas by adding gums during extrusion to obtain nixtamalised corn flour. Journal of Texture Studies. 2010;**41**:736-755

[58] Hasjim J, Li E, Dhital S. Milling of rice grains: The roles of starch structures in the solubility and swelling properties of rice flour. Starch-Stärke. 2012;**64**:631-645

[59] Sahai D, Buendía MO, Jackson DS. Analytical techniques for understanding nixtamalized corn flour: Particle size and functionality relationships in a masa flour sample. Cereal Chemistry. 2001;**78**:14-18

[60] Paredes-López O, Saharópulos-Paredes ME. Scanning electron microscopy studies in limed corn. Journal of Food Science Technology. 1983;**17**:687-693

[61] Wen LF, Rodis P, Wasserman BP. Starch fragmentation and protein insolubilization during twin-screw extrusion of corn meal. Cereal Chemistry. 1990;**67**:268-275

[62] Harper JM. Extrusion of foods. In: IFT Symposium Series: Biotechnology and Food Process Engineering; 1990. pp. 295-308

[63] Camire ME, Camire A, Krumhar K. Chemical and nutritional changes in foods during extrusion. Critical Reviews in Food Science and Nutrition. 1990;**29**:35-57

[64] Charbonniere R, Duprat F, Guibolt A. Changes in various starches by extrusion cooking 2: Physical structures of extruded products. Cereal Science Today. 1973;**l8**:286

[65] Chinnaswamy R, Hanna MA. Macromolecular and functional properties of native and extrusion-cooked corn starch. Cereal Chemical 1990;**67**:490-499

[66] Kljak K, Šárka E, Dostálek P, Smrčková P, Grbeša D. Influence of physicochemical properties of Croatian maize hybrids on quality of extrusion cooking. LWT-Food Science and Technology. 2015;**60**:472-477

[67] Curic D, Novotni D, Bauman I, Kricka T, Dugum J. Optimization of extrusion cooking of cornmeal as raw material for bakery products. Journal of Food Process Engineering. 2009;**32**:294-317

[68] Platt-Lucero LC, Ramírez-Wong B, Torres-Chávez PI, López-Cervantes J, Sánchez-Machado DI, Carvajal-Millán E, Morales-Rosas I. Effect of xylanase on extruded nixtamalised corn flour and tortilla: Physicochemical and rheological characteristics. Journal of Food Process Engineering. 2013;**36**:179-186

[69] Bhattacharya M, Hanna MA. Kinetics of starch gelatinization during extrusion cooking. Journal of Food Science 1987;**52**:764-766

[70] Lawton BT, Henderson GA, Derlatka EJ. The effects of extruder variables on the gelatinization of corn starch. Canadian Journal of Chemical Engineering. 1972;**250**:168-172

[71] Bazúa CD, Guerra R, Sterner H. Extruded corn flour as an alternative to lime-heated corn flour for tortilla preparation. Journal of Food Science. 1979;**44**:940-941

[72] González-Vera I. Evaluación de cambios fisicoquímicos que sufre el almidón en el proceso de elaboración de tortillas, utilizando harinas nixtamalizadas por extrusión de maíz de alta calidad proteica (Thesis). Hermosillo, Sonora, México: University of Sonora; 2006

[73] Arámbula-Villa G, González-Hernández J, Moreno ME, Ordorica Falomir CA. Characteristics of tortillas prepared from dry extruded masa flour added with maize pericarp. Journal of Food Science. 2002;**67**:1444-1448

[74] Gómez-Aldapa C, Martínez-Bustos F, Figueroa-Cárdenas JD, Ordorica FCA. A comparison of the quality of whole corn tortillas made from instant corn flours by traditional or extrusion processing. International Journal of Food Science Technology. 1999;**34**:391-399

[75] Kokini JL, Baumann GC, Bresslauer K, Chedid LL, Herh P, Lai LS, Medeka H. A kinetic model for starch gelatinization and effect of starch/protein interactions on rheological properties of 98% amylopectin and amylose rich starches. Engineering and Foods: Advanced Process. Spiess, Schubert, Eds; Elsevier / Applied Science Publishers, NY USA 1990; Vol. 1, pp. 109-121.

[76] Gómez-Aldapa C, Martínez-Bustos F, Figueroa-Cárdenas JD, Ordorica-Falomir CA, González Hernández J. Chemical and nutritional changes during preparation of whole corn tortillas prepared with instant flour obtained by extrusion process. Archivo Latinoamericano de Nutrición. 1996;**46**:315-319

[77] Milán-Carrillo J, Gutiérrez-Dorado R, Perales-Sánchez JXK, Cuevas-Rodríguez EO, Ramírez-Wong B, Reyes-Moreno C. The optimization of the extrusion process when using maize flour with a modified amino acid profile for making tortillas. International Journal of Food Science and Technology. 2006;**41**:727-736

[78] Balandran-Quintana RR, Barbosa-Canovas GV, Zazueta-Morales JJ, Anzaldúa-Morales A, Quintero-Ramos A. Functional and nutritional properties of extruded whole pinto bean meal (*Phaseolus vulgaris* L.). Journal of Food Science. 1998;**63**:113-116

[79] Pérez AA, Drago SR, Carrara CR, De Greef, DM, Torres RL, González RJ. Extrusion cooking of a maize/soybean mixture: Factors affecting expanded product characteristics and flour dispersion viscosity. Journal of Food Engineering. 2008;**87**:333-340

[80] Hagenimana A, Ding X, Fang T. Evaluation of rice flour modified by extrusion cooking. Journal of Cereal Science. 2006;**43**:38-46

[81] Wolf B. Polysaccharide functionality through extrusion processing. Current Opinion in Colloid and Interface Science. 2010;**15**:50-54

[82] Martinez-Bustos F, Sanchez-Sinencio F, Gonzalez-Hernandez J, Martinez JD, Ruiz-Torres M. U.S. Patent No. 5532013. Washington, DC: U.S. Patent and Trademark Office; 1996

[83] Gutiérrez-Dorado R, Ayala-Rodríguez AE, Milán-Carrillo J, López-Cervantes J, Garzón-Tiznado JA, López-Valenzuela JA, Reyes-Moreno C. Technological and nutritional properties of flours and tortillas from nixtamalized and extruded quality protein maize (*Zea mays L.*). Cereal Chemistry. 2008;**85**:808-816

[84] Ghodke SK, Ananthanarayan L, Rodríguez L. Use of response surface methodology to investigate the effects of milling conditions on damaged starch, dough stickiness and chapatti quality. Food Chemistry. 2009;**112**:1010-1015

[85] Arámbula-Villa G, González-Hernández J, Ordorica-Falomir CA. Physicochemical, structural and textural properties of tortillas from extruded instant corn flour supplemented with various types of corn lipids. Journal of Cereal Science. 2001;**33**:245-252

[86] Al-Okbi SY, Hussein A, Hamed IM, Mohamed DA, Helal AM. Chemical, rheological, sensorial and functional properties of gelatinized corn-rice bran flour composite corn flakes and tortilla chips. Journal of Food Processing and Preservation. 2014;**38**:83-89

[87] Colonna P, Tayeb J, Mercier C. Extrusion cooking of starch and starchy products. In: Mercier C, Linko P, Harper LM editors. Extrusion Cooking. USA: AACC; 1989. pp. 247-319

[88] Arámbula-Villa G, Figueroa-Cárdenas JD, Martinez-Bustos F, Ordorica-Falomir CA, Gonzalez-Hernandez J. Milling and processing parameters for corn tortillas from extruded instant dry masa flour. Journal of Food Science. 1998;**63**:338-341

[89] Ignacio RM, Lannes SC. Rheological characterization and texture of commercial mayonnaise using back extrusion. African Journal of Agriculture Research. 2013;**8**:4262-4268

[90] Limanond B, Castell-Perez E, Moreira RG. Effect of time and storage conditions on the rheological properties of masa for corn tortillas. LWT-Food Science Technology. 1999;**32**:344-348

[91] Steffe J F. Rheological methods in food process engineering. 2nd ed. Freeman Press. 2807 Still Valley Dr. East Lansing MI USA 1996; pp. 255-258, 294-310.

[92] Karim AA, Norziah MH, Seow CC. Methods for the study of starch retrogradation. Food Chemistry. 2000;**71**:9-36

[93] Flores-Farías R, Martínez-Bustos F, Salinas-Moreno Y, Chang YK, Hernández JG, Ríos E. Physicochemical and rheological characteristics of commercial nixtamalised Mexican maize flours for tortillas. Journal of Science Food Agriculture. 2000;**80**:657-664

[94] Ramaswamy HS, Singh A, Sharma M. Back extrusion rheology for evaluating the transitional effects of high pressure processing of egg components. Journal of Texture Studies. 2015;**46**:34-45

[95] Ditudompo S, Takhar PS, Ganjyal GM, Hanna MA. The effect of temperature and moisture on the mechanical properties of extruded corn starch. Journal of Texture Studies. 2013;**44**(3):225-237

[96] Engmann J, Servais C, Burbidge AS. Squeeze flow theory and applications to rheometry: A review. Journal of Non-Newtonian Fluid Mechanics. 2005;**132**:1-27

[97] Corradini MG, Peleg M. Consistency of dispersed food systems and its evaluation by squeezing flow viscometry. Journal of Texture Studies. 2005;**36**:605-629

[98] Vázquez-Carrillo MG, Santiago-Ramos D, Gaytán-Martínez M, Morales-Sánchez E, Guerrero-Herrera JM. High oil content maize: Physical, thermal and rheological properties of grain, masa, and tortillas. LWT-Food Science Technology. 2015;**60**:156-161

[99] Ramírez-Wong B, Walker CE, Ledesma-Osuna AI, Torres-Chávez PI, Medina-Rodríguez CL, López-Ahumada GA, Flores RA. Effect of flour extraction rate on white and red winter wheat flour compositions and tortilla texture. Cereal Chemistry. 2007;**84**:207-213

[100] Chaidez-Laguna LD, Torres-Chavez PI, Ramírez-Wong B, Marquez-Ríos E, Islas-Rubio AR, Carvajal-Millan E. Corn proteins solubility changes during extrusion and traditional nixtamalisation for tortilla processing: A study using size exclusion chromatography. Journal of Cereal Science. 2016;**69**:351-357

[101] Reyes-Moreno C, Ayala-Rodríguez AE, Milán-Carrillo J, Mora-Rochín S. Production of nixtamalized flour and tortillas from amaranthine transgenic maize lime-cooked in a thermoplastic extruder. Journal of Cereal Science. 2013;**58**:465-471