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IMPACT OF NIXTAMALIZATION ON THE NUTRITIONAL AND FUNCTIONAL PROPERTIES OF CORN-BASED PRODUCTS: A REVIEW

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ABSTRACT

Nixtamalization, a traditional alkaline cooking process, plays a crucial role in enhancing the nutritional, functional, and sensory properties of maize-based products. This review explores the fundamental principles of nixtamalization, its impact on maize composition, and the technological advancements improving its sustainability and nutritional outcomes. The process enhances the bioavailability of essential nutrients such as niacin, calcium, and iron while reducing anti-nutritional factors and contaminants like mycotoxins and acrylamide. Additionally, ecological nixtamalization (EN) has emerged as a sustainable alternative to conventional processing, reducing environmental impact while preserving nutritional benefits. Fortification strategies further enhance the nutritional quality of nixtamalized products, addressing micronutrient deficiencies and offering functional health benefits. This review also examines the physicochemical changes in starch, protein, and fiber during nixtamalization, along with their impact on food texture, stability, and sensory attributes. By integrating recent research findings, this paper highlights innovations in nixtamalization that contribute to the development of healthier and more sustainable maize-based food products.
***Keywords* :** Corn, Ecological, Masa, Nixtamalization, Tortilla, Traditional.

Introduction

Tortillas are deeply rooted in Mesoamerican traditions, particularly among indigenous Mexican cultures such as the Aztecs and Mayans, dating back thousands of years. These civilizations relied heavily on maize and developed various methods to process and consume it. One of the most significant advancements in maize processing was nixtamalization, a technique that involves soaking and cooking maize in limewater (calcium hydroxide) to enhance its nutritional profile and facilitate grinding. This method, which dates back to approximately 1500 BCE, remains essential for producing tortilla masa (dough).

With the arrival of Spanish colonists in the early 16th century, tortillas quickly became a staple in their diet. The Spanish introduced the term "tortilla," derived from "torta," meaning "cake" (Coe, 1994). Over time, European ingredients and techniques influenced tortilla-making, yet the traditional maize tortilla retained its prominence. The 20th century witnessed significant changes with the mechanization of tortilla production, which improved efficiency, accessibility, and affordability (Pilcher, 1998). Today, tortillas remain a cornerstone of Mexican cuisine and have gained widespread popularity, particularly in the United States, where both maize and flour tortillas are consumed extensively.

Tortilla chips, a modern adaptation of tortillas, emerged in the 1940s in the United States. Rebecca Webb Carranza is credited with popularizing tortilla chips, transforming them into a widely consumed snack. The preparation of maize through nixtamalization not only enhances its flavor and nutritional value but also increases its versatility. However, traditional nixtamalization presents challenges, including high water and fuel consumption, waste generation, soil alkalinization, and nutrient loss. To address these concerns, ecological nixtamalization has been developed as a sustainable alternative that reduces resource use and minimizes environmental impact.

The global tortilla market has experienced substantial growth, driven by the rising demand for Mexican and Tex-Mex cuisine. Market research valued the tortilla industry at approximately USD 40 billion in 2021, with a projected compound annual growth rate (CAGR) of 5-6% from 2022 to 2028. North America, particularly the United States, remains the largest market for tortillas, while Latin America and Europe also demonstrate significant demand for ethnic and health-conscious food products.

Maize plays a critical role in global food security. According to the Food and Agriculture Organization (FAO), global maize production reached 1.1 billion metric tonnes in 2020, with the United States, China, and Brazil as the leading producers. The world consumed approximately 1.15 billion metric tonnes of maize in 2020, with the majority being used for animal feed and ethanol production. India, the fifth-largest maize producer, contributes around 2.59% of global production and primarily cultivates maize year-round. APEDA estimated India's maize production at 35.91 million metric tonnes in 2022-23, with exports reaching 3.45 million metric tonnes (Xu *et al.,* 2010).

From a nutritional perspective, maize consists predominantly of carbohydrates (72-73%) and contains moderate amounts of protein (7-9%) and fat (3-4%). It is a good source of thiamine (B_1), niacin (B_3), and folate (B_9) and contains trace amounts of vitamin E. The insoluble fiber in maize aids digestion, while its antioxidants, including lutein and zeaxanthin, contribute to eye health and may reduce the risk of chronic diseases. However, maize has some limitations, including a deficiency in lysine and tryptophan, making its protein content inferior to that of other crops (Rolandelli *et al.,* 2024).

Tortillas are often considered a healthier alternative to bread, leading to the development of gluten-free and low-carb varieties made from almond flour, coconut flour, and other substitutes. Although tortilla chips are commonly perceived as a snack, they can be nutritious when consumed in moderation and prepared with wholesome ingredients. Whole corn tortilla chips provide dietary fiber, help regulate blood sugar levels, and are naturally gluten-free, making them suitable for individuals with celiac disease. The incorporation of beans into tortilla chips further enhances their nutritional profile by adding essential amino acids and bioactive compounds (Mendez *et al*., 2013).

Despite the widespread consumption of maize, there are limited reports on the combination of maize with other nutrient-rich ingredients for tortilla chip production. Given the potential health benefits and nutritional improvements, this study aims to develop tortilla chips using enhanced formulations. By leveraging the complementary nutritional profiles of various ingredients, the study seeks to create a healthier alternative to conventional tortilla chips, catering to evolving consumer preferences for functional and nutritious snack options.

Nixtamalization

Nixtamalized maize products are made using three fundamental ingredients: maize kernels, water, and lime (calcium hydroxide). Additional additives like hydrocolloids, emulsifiers, and enzymes are sometimes used to extend shelf life and improve textural qualities (Ochoa *et al.,* 2016). The nixtamalization process involves lime-cooking maize kernels, steeping them, and washing to form *nixtamal*, which is ground into masa (dough). This masa serves as the base for tortillas and various snacks. Lime-cooking plays a critical role as it facilitates pericarp removal, enhances starch gelatinization, and improves dough cohesiveness. For tortillas, the nixtamal is finely ground into masa with 56–60% moisture content, while coarser masa with 50–54% moisture is used for snack production. Tortilla baking involves shaping masa into thin discs and baking them at high temperatures (280–302°C). This process not only inactivates microbes but also develops the characteristic texture, color, and flavor of tortillas. Alternatively, dry masa flour (DMF) is produced by grinding nixtamal without steeping, followed by dehydration and sieving. DMF has a long shelf life, making it ideal for tortillas and chips globally (Serna-Saldivar, 2021).

The nixtamalization process induces significant functional changes in maize components. During lime-cooking, starch gelatinizes partially, improving masa cohesiveness, while proteins undergo denaturation, and lipids interact with amylose, enhancing flavor but becoming prone to oxidation. Dietary fiber also changes-crude fiber decreases while soluble fiber, particularly arabinoxylans, increases, contributing to improved textural properties in tortillas. Nixtamalized products include popular snacks like corn chips and tortilla chips. Corn chips are produced by extruding masa, while tortilla chips are pre-baked, cooled, and fried to achieve crispiness with lower oil uptake. Pre-baking reduces moisture, which minimizes oil absorption during frying. Compared to corn chips, tortilla chips absorb 12% less oil, making them a lower-calorie snack option (Rojas-Molina *et al.*, 2024).

The primary benefit of nixtamalization lies in its ability to increase the nutritional value of maize. It liberates bound niacin, making it bioavailable and preventing conditions like pellagra, which arises from niacin deficiency. Additionally, nixtamalization reduces anti-nutritional factors like phytic acid, which otherwise hinder mineral absorption, and it enhances the levels of ionizable calcium, iron, and zinc (Burns *et al*., 2021). This process also decreases the presence of harmful mycotoxins, particularly aflatoxins, by up to 90–94%, making nixtamalized grains safer for consumption. Furthermore, nixtamalization minimizes the formation of acrylamide, a carcinogenic compound, in fried and baked maize products. The calcium uptake during the process increases grain crispiness, improving the texture and sensory qualities of products like tortillas and snacks (Pandey and Waghmare 2019).

Nixtamalization also induces color changes in the pericarp, turning it yellow due to the transformation of flavonoid pigments under alkaline conditions. Lignin oxidation, though minimal, further contributes to this yellowing effect. Within the endosperm, the first noticeable change is hydration, where water diffuses into the spaces between starch granules, causing them to swell. Water absorption is faster during cooking and the initial steeping period, with soft grains hydrating more quickly due to their loosely packed starch granules compared to the denser structure of hard grains. Starch undergoes partial gelatinization primarily in the outer layers of the endosperm (10–20%) due to cooking temperatures exceeding 70°C. The inner endosperm layers remain largely intact but experience annealing during steeping, a process where molecular realignment strengthens the crystalline structure, increasing starch gelatinization temperatures (Santiago-Ramos, 2018).

The interaction between calcium ions and starch is another critical change. In alkaline conditions, calcium bridges form between amylose and amylopectin chains, stabilizing the starch granules and enhancing their thermal and structural properties. Additionally, nixtamalization promotes the formation of amylose-lipid complexes, particularly Type II complexes, which are more ordered and stable. These complexes arise when amylose leaches from gelatinized starch and interacts with free lipids, further contributing to the structural stability of starch. Starch crystallinity decreases initially due to partial gelatinization but is partially restored through annealing during steeping. These changes influence the pasting properties of starch, increasing its viscosity and thermal stability due to calcium crosslinks. Furthermore, the process leads to a slight decrease in starch digestibility as resistant starch (RS) forms, including RS5 (amylose-lipid complexes) and RS3 (retrograded starch), which offer additional nutritional benefits (Santiago-Ramos 2018).

The reviewed studies highlight significant advancements in the physicochemical properties and processing techniques of maize and starch-based products. Research on starch structure emphasizes the role of amylopectin chain-length distribution in retrogradation, influencing food texture, stability, and nutritional properties (Chang *et al.*, 2021). Innovations in nixtamalization, including ohmic heating (OH), extrusion wet milling (EWMN), and alkaline extrusion, have improved the functional, rheological, and nutritional qualities of masa and corn-based doughs, enhancing starch gelatinization, water absorption, and textural stability (Dominguez *et al.*, 2024; Enríquez et al., 2024). Studies on resistant starch (RS2) formation in tortillas suggest that nixtamalization contributes to an increase in nutritional benefits such as glycemic control and gut health (Rojas *et al.*, 2024).

Beyond traditional nixtamalization, researchers have explored alternative ingredients and formulations to improve tortilla quality and nutritional composition. The incorporation of soybean and voandzou flours has been found to enhance protein content, adhesiveness, and rheological properties, making white masa-soybean blends optimal for tortilla production (Dongmo *et al.*, 2024). Similarly, pomegranate peel powder (PPP) has been shown to extend shelf life and antioxidant activity in tortilla chips while maintaining sensory acceptability (Vasisht *et al.*, 2024). In gluten-free applications, alkaline deamidation of zein with pea protein isolate (PPI) improves the viscoelasticity and dough stability, offering promising solutions for gluten-free bakery products (Rolandelli *et al.*, 2024).

The impact of nixtamalization on nutrient bio accessibility and consumer preferences has also been extensively studied. Traditional nixtamalization (NMT) preserves anthocyanin content and enhances antioxidant activity in blue maize tortillas compared to extrusion nixtamalization (EMT), reinforcing its health benefits and importance in tortilla production (Gaxiola *et al*., 2025). Similarly, native Mexican landrace tortillas contain higher calcium and lower sodium than commercial tortillas, making them nutritionally superior (Salinas *et al*., 2024). Additionally, research on sorghum and maize-based gluten-free bread indicates that nixtamalization enhances antioxidant properties and consumer acceptance, further supporting its functional benefits in gluten-free applications (Mariscal *et al*., 2024).

Lastly, sustainability in maize processing has been addressed through the use of alternative alkaline agents and wastewater bioremediation. Studies demonstrate that wood ash, maize cob ash, and tequesquite can serve as substitutes for lime in regions with limited calcium hydroxide availability, though adjustments in processing times are necessary (Vázquez *et al*., 2024). Meanwhile, the application of alkali-tolerant yeast (*Rhodotorula mucilaginosa LCRE*) has shown potential for cost-effective nejayote treatment, reducing chemical oxygen demand (COD) and pH levels while producing valuable microbial biomass (Roman *et al*., 2024). These findings underscore the interplay between processing techniques, nutritional enhancement, and environmental sustainability, shaping the future of maize-based food production.

Tortilla chips

Tortilla chips are a popular snack made from nixtamalized corn dough, commonly known as masa. Nixtamalization involves cooking and steeping corn in an alkaline solution, which is then ground to create a soft dough. This dough is shaped into tortillas, baked to reduce moisture, and subsequently fried to produce the crispy texture that defines tortilla chips. During frying, significant changes occur in the structure of the chips. Gutierrez-Salomon *et al.* (2020) The diameter shrinks due to moisture loss, while the thickness expands slightly as steam and gases cause bubbles to form. These structural changes lead to an increase in porosity, creating a light, open texture with larger and more uniform pores over time. The combination of moisture evaporation, oil absorption, and pore formation is critical to achieving the chips' signature crunchiness (Kawas and Moreira, 2001).

Moisture loss is rapid in the initial stages of frying, particularly within the first 15 seconds, where most shrinkage and structural changes take place. As the frying process continues, oil absorption increases, with tortilla chips eventually containing around 20-30% oil by weight. A substantial portion of this oil is absorbed during cooling, which further influences the final texture and quality. The chips' glass transition temperature (Tg), a measure of physical state changes based on moisture and oil content, plays a critical role in maintaining product stability. Storing tortilla chips at temperatures below their Tg ensures they remain in a crisp, glassy state, preserving their texture and extending shelf life (Ochoa *et al*., 2016).

The frying process not only alters the chips' structure but also determines their quality attributes, including shrinkage, expansion, puffiness, and texture. Research shows that as frying progresses, the chips become crunchier due to the formation of a porous network and a reduction in moisture content. Kaur *et al*. (2017) Models such as the Crapiste and Rotstein equation or the extreme value distribution have been used to predict changes in moisture loss, pore size distribution, and structural development during frying. These findings highlight the importance of controlling frying conditions to produce high-quality tortilla chips with the desired crunch, texture, and oil content (Chhabra *et al*., 2017).

The textural properties of tortilla chips are significantly influenced by the conditions under which they are produced, particularly during the baking and frying processes. Texture, a critical quality attribute, was evaluated using instrumental methods to measure properties such as hardness, crunchiness, and fracturability. These parameters provide essential insights into the chips' overall eating quality. Baking temperature, in particular, plays a major role in determining texture. Higher baking temperatures, result in firmer and crisper chips due to accelerated moisture loss and enhanced surface browning (Kayacier and Singh 2003).

Fracturability, which refers to how easily a chip breaks under applied force, increases with baking temperature as the chips become more brittle. This is closely related to moisture loss during baking, which leads to a rigid and dry structure. Similarly, hardness, measured as the peak force required to break the chip, also increases under higher heat conditions. Crunchiness, another key textural characteristic, is strongly linked to the development of a porous structure. As chips lose moisture and air pockets form, their ability to produce a distinct cracking sound when bitten improves, enhancing the perception of crunchiness (Messina *et al*., 2024).

The structural changes that occur during baking are critical to the textural properties of tortilla chips. The formation of pores and crust, particularly at higher temperatures, leads to a more uniform and well-developed porous network. This not only enhances the mechanical properties of the chips but also contributes to their overall texture and appeal. In conclusion, optimizing baking conditions is essential to produce tortilla chips with the desired texture, characterized by a balance of hardness, crunchiness, and fracturability, which ultimately enhances their consumer acceptability (Mareira *et al*., 1997).

The study reveals that oil uptake in tortilla chips is influenced by several factors, including initial moisture content, particle size distribution, and oil quality. Higher initial moisture content and smaller particle size resulted in increased oil absorption due to the development of pore structures and high capillary pressure within the pores during cooling. Interestingly, the rate of oil uptake was independent of frying oil temperature, and while the total final oil content was unaffected by oil quality, chips fried in used oil showed more surface oil accumulation due to its higher viscosity and lower surface tension. The study found that only 20% of the total oil content was absorbed during frying, while 64% was absorbed during cooling, with the remaining 36% adhering to the chip's surface. These findings emphasize the importance of controlling processing parameters to manage oil absorption and ensure the quality of tortilla chips (Moreira *et al.,* 1997).

The drying process significantly affects the textural and sensory attributes of tortilla chips. A study by Puspantari *et al.* (2024) evaluated different drying times (60, 90, and 120 minutes) at 50°C for tortillas of varying thicknesses (2mm and 4mm). Results showed that 90 minutes of drying produced the crispiest tortillas with optimal fracturability (651.30g for 2mm and 767.00g for 4mm). Moisture content decreased with longer drying times, while oil content ranged between 9.06% and 12.11% after frying. Thicker tortillas retained more moisture, requiring extended drying times.

Beyond traditional deep frying, alternative frying oils have been studied for their health benefits. Buzgău *et al*. (2022) examined high oleic sunflower oil (HOSO) in tortilla chip frying, finding that its higher oleic acid content (84%) improved oxidative stability, reduced oil degradation, and extended shelf life. These findings highlight the potential of process optimization in reducing oil absorption while enhancing texture and consumer appeal.

Traditional process

The traditional nixtamalization process (TNP) is an essential pre-Columbian method for transforming corn into food products such as tortillas, tamales, and snacks, playing a vital role in enhancing the nutritional and sensory properties of corn-based foods. By cooking corn in an alkaline solution, typically calcium hydroxide, TNP facilitates physical and chemical transformations that improve the bioavailability of nutrients like calcium, enhance flavor, and create the desirable texture and shelf stability of products. Despite its benefits, TNP has significant drawbacks. The process generates large amounts of alkaline wastewater, known as nejayote, which contains starch, proteins, and other organic compounds that contribute to environmental pollution. Additionally, TNP is resource-intensive, requiring substantial amounts of water and energy, making it less sustainable. It also leads to nutrient loss, as the washing and cooking steps can strip the corn of essential nutrients and bioactive compounds. While alternative technologies have been developed to address these issues, such as reducing effluent generation or improving energy efficiency, many struggle to replicate the unique qualities of products made using the traditional method. Despite its environmental and resource challenges, TNP remains a cornerstone of traditional cuisine, valued for producing high-quality, culturally significant food products (Rojas-Molina *et al.*, 2020).

The traditional nixtamalization process is critical for converting corn into staple foods like tortillas, tamales, and fried snacks, primarily in Central America, Mexico, and the southern United States. This process involves a multi-step procedure, including cooking, steeping, wet milling, and baking. Nixtamalization enhances the physicochemical properties of corn through structural, thermal, and morphological changes, resulting in products with improved texture, flavor, and nutritional value (Villada, 2017).

The process facilitates the dissolution of hemicellulose and the transformation of cellulose into alkaline cellulose and other crystalline forms. This structural modification improves the quality of the masa (corn dough) and the final product. Additionally, the alkaline treatment enables the infusion of calcium, enhancing the nutritional profile of the corn. Al-Okbi *et al.* (2014) Despite modern alternatives like instant corn flour, traditional nixtamalization remains integral to producing tortillas with superior organoleptic properties, meeting the high-quality standards of traditional cuisine (Briones, 2000).

Additionally, the crystalline structure of starch in the outer layers is disrupted, which enhances the functional and storage qualities of the grain. This method not only supports large-scale production while preserving traditional qualities but also offers cultural significance in regions like Mexico, Central America, and parts of the United States (Márquez-Sandoval *et al*. (2014). Scientific analyses, such as X-ray diffraction and differential scanning calorimetry, have further demonstrated the process's ability to optimize starch recrystallization and structural properties, making nixtamalization an indispensable technique in maize processing (Rojas-Molina, 2007).

Ecological process

The ecological nixtamalization (EN) process is a significant advancement in traditional food processing, offering both environmental and nutritional benefits. Unlike the traditional method, which uses calcium hydroxide ($Ca(OH)_2$) and generates alkaline wastewater, the EN process employs calcium salts such as calcium chloride ($CaCl_2$), calcium carbonate ($CaCO_3$), and calcium sulfate ($CaSO_4$). These alternatives produce wastewater with a lower pH (4.3–7.3) and reduced pollutant content, making the process more environmentally sustainable (Lagunas, 2022).

Nutritionally, the EN process maintains or enhances the content and bioaccessibility of phenolic compounds (PCs) in tortillas, particularly anthocyanins, which are valued for their antioxidant properties. EN retains more phenolic compounds compared to traditional methods, with some treatments showing higher bioaccessibility of these bioactive compounds across digestive stages. This increased bioavailability is critical for the potential health benefits of tortillas, including the reduction of chronic diseases due to antioxidant effects (Santiago-Ramos *et al*., 2015).

Furthermore, the EN process reduces the loss of phenolic compounds during nixtamalization by minimizing the extreme pH and temperature conditions that typically degrade these compounds in traditional methods. This not only preserves the nutritional quality of the tortillas but also contributes to the sustainability of the nixtamalization process. By combining environmental benefits with enhanced nutritional outcomes, the ecological nixtamalization process represents a modern, sustainable evolution of an ancient culinary tradition (Campechano Carrera *et al*., 2012).

From a nutritional standpoint, tortillas produced through ENP exhibit enhanced dietary fiber and resistant starch content, which contribute to a lower glycemic index. Furthermore, the process reduces starch retrogradation and staling during storage (Maya-Cortes *et al*., 2010). This leads to improved textural properties, as tortillas made with ENP retain moisture better and exhibit reduced hardness over time compared to traditional methods. These characteristics not only enhance consumer acceptance by maintaining tortilla freshness but also reduce food waste, addressing significant economic and sustainability challenges in the tortilla industry (Mariscal-Moreno, 2022).

ENP's ability to preserve and enhance both the quality and environmental sustainability of tortilla production marks it as a modern improvement to the ancient nixtamalization tradition, aligning with contemporary needs for sustainable and health-conscious food processing (Mariscal-Moreno, 2022).

Advancements in nixtamalization aim to improve sustainability while maintaining product quality:

- **Alternative ingredients and functional flours**: Research has evaluated novel formulations, such as tortilla chips fortified with sunflower seeds (Suryawan *et al*., 2022) and gluten-free sorghum blends (Messina *et al.*, 2024), to enhance nutritional value and cater to dietary restrictions.
- **Organic vs. non-organic comparisons**: White *et al.* (2023) conducted GC-MS and PCR analyses on 20 tortilla chip brands, finding that all organic samples were GMO-free, whereas 90% of nonorganic chips contained genetically modified components. Despite minor chemical differences, consumers perceived organic chips as healthier and were willing to pay a premium.
- **IoT and Smart Processing**: Thayyib *et al*. (2023) explored an IoT-based tortilla chip-cutting monitoring system using ESP32 microcontrollers, demonstrating improved efficiency and real-time data collection in food manufacturing.
- The effect of Nixtamalization on nutrient/ component of food item is shown in Table 1.

Fortification

Fortification has a significant impact on the nutritional profile of tortilla chips, enhancing their value as a staple food. The use of fortified nixtamalized corn flour (NCCF) increases the levels of essential micronutrients like iron, zinc, and folic acid. For instance, tortillas made from a 50:50 mix of traditional nixtamalized masa (NM) and NCCF provide over 100% of the recommended daily intake (RDI) of folic acid for children and adults. However, traditionally prepared tortillas (NC-T) exhibit a higher calcium content due to the prolonged soaking process in lime water, which facilitates calcium absorption into the corn. Additionally, fortification improves protein quality, with in vitro protein digestibility being about 10% higher in fortified tortillas compared to traditional ones. This improvement is linked to differences in the processing conditions of the two methods (Mendez *et al*., 2013). The health benefits of nixtamalization are discussed in Table 2.

Previous studies, including the research by Syarifah and Amrih (2021), Rojas *et al.* (2024), Salinas *et al*. (2024, Gaxiola *et al*. (2025), Buzgau *et al*. (2022), Mariscal-Moreno (2022), have found that nixtamalization significantly enhances the nutritional profile of corn by improving mineral absorption, reducing mycotoxins, and increasing dietary fiber. These findings are consistent with other research indicating similar benefits in terms of digestibility, gut health, and antioxidant activity.

Fortified tortillas also show a slight increase in resistant starch (RS) content, which contributes to dietary fiber and supports gut health, though total starch content remains similar between fortified and traditional versions. Beyond nutritional enhancement, fortified tortillas play a critical role in addressing widespread micronutrient deficiencies in the Mexican population, particularly in iron and zinc. A 50:50 mixture of NM and NCCF contributes significantly to the RDI for these minerals, as well as for magnesium and calcium, varying by age group. This makes fortification a practical strategy for improving public health without altering dietary habits (Nieves-Hernandez *et al*., 2024).

The fortification of maize tortilla chips with optimized chickpea hydrolysate has shown a significant impact on their nutritional and functional properties. One of the key benefits is the increased inhibition of dipeptidyl peptidase-IV (DPPIV), which is relevant for managing type 2 diabetes. Fortified tortillas exhibited a DPPIV inhibition capacity of up to 95% in blue maize tortillas and 91% in white maize tortillas at the highest fortification level (15%). This indicates the potential of these fortified products in extending postprandial insulin action and supporting diabetes management (Acevedo-Martinez *et al* 2021).

Additionally, fortification led to an increase in soluble protein content, enhancing the overall protein quality of the tortillas. For instance, white maize tortillas fortified with 15% chickpea hydrolysate showed an increase in soluble protein concentration from 4.02 g/100 g to 13.06 g/100 g. Despite these benefits, some changes in physicochemical properties, such as texture, moisture retention, and color, were observed. Higher fortification levels influenced hardness and cohesiveness, and slight differences in moisture retention were noted during storage (Acevedo-Martinez *et al*., 2021).

Fortification of tortilla chips with chickpea and red lentil flours significantly enhances their nutritional profile, making them a richer source of protein and essential fatty acids like linoleic and gamma-linolenic acids, while maintaining their sensory and textural appeal. The protein content increased notably, reaching up to 22.79% in chips with 100% red lentil flour, and unsaturated fatty acids accounted for up to 90% of total fats (Garcia-Rojas *et al*., 2024). Moisture and fat content also rose with fortification, while peroxide values showed varied trends decreasing with lentil flour and increasing with chickpea flour. The aroma profile, dominated by aldehydes, ketones, and alcohols, was enriched, contributing to consumer acceptability. These findings highlight the potential of legume-enriched tortilla chips as healthier snack options without compromising on quality (Buzgau *et al*., 2023).

The impact of fortification on tortilla chips, as discussed in the paper, involves altering their physical and nutritional properties by incorporating different types of vegetable flour. Fortification with flours such as chickpea, lentil, or others affects the chips' texture, moisture content, and nutritional profile, potentially enhancing their protein levels and adding dietary fiber. These modifications aim to create healthier alternatives to traditional tortilla chips while maintaining desirable sensory qualities. However, the specific effects on properties such as crispiness, oil absorption, and flavor would depend on the type and proportion of vegetable flour used (Syarifah and Amrih, 2021)

Fortifying tortilla chips with mango peel (MP) and decocted roselle calyx (DRC) powders enhances their nutritional and functional properties, offering a healthier snack option. The addition of MP and DRC significantly increases dietary fiber content, meeting daily intake recommendations, while also boosting antioxidant levels through higher phenolic compound content. This fortification reduces the glycemic index (GI), particularly at 10% MP or DRC, aiding glucose regulation and metabolic health. Additionally, pre-frying dehydration lowers fat absorption by 58%, creating a low-fat alternative. While MP-enhanced chips maintain good sensory appeal, DRC chips show potential for improvement with seasoning, making this approach an effective use of agro-industrial by-products for creating nutritious tortilla chips (Mariscal-Moreno *et al.* 2022).

Fortification has emerged as a key strategy for improving the nutritional profile of tortilla chips. Various studies have explored ingredient modifications to enhance protein, fiber, and essential fatty acids:

- **Legume-Based Fortification**: Incorporating chickpea and red lentil flour in varying proportions (20%, 50%, 80%, and 100%) increased protein content while maintaining sensory acceptability (Buzgau *et al.*, 2023). However, higher concentrations also increased moisture and fat content. A 50% chickpea flour blend was identified as optimal for balancing nutrition and texture.
- **Tempeh-Enriched Chips**: Indriyanim *et al*. (2023) tested corn-tempeh flour blends (ranging

from 100:0 to 50:50) to address childhood stunting. While the 50% tempeh formulation had the highest protein and calcium content, the 10% blend was most preferred in sensory evaluation.

- **Functional Ingredients**: Moringa seed flour was tested as a protein and micronutrient enhancer in corn tortillas. Substituting 5-15% of corn flour with moringa improved protein content (from 4.00% to 7.42%) and fiber levels (from 2.63% to 4.49%), with the 5% substitution yielding the best consumer acceptance (Nur *et al*., 2022). The benefits of nixtamalization are discussed in Table 3.

Challenges

The production and marketing of tortilla chips face challenges across multiple fronts, including ensuring ingredient quality, maintaining consistent texture and flavor, and meeting health-conscious demands with low-fat or fortified options. Manufacturing processes must address high costs, food safety compliance, and sustainable waste management, especially when incorporating alternative ingredients. In a crowded market, brands struggle to differentiate themselves, educate consumers on the benefits of healthier options, and adapt products to diverse cultural preferences. Selling challenges include pricing pressure, distribution complexities, and securing shelf space in competitive retail environments. Additionally, evolving consumer behaviors such as the preference for health-focused snacks, sensitivity to pricing, demand for sustainability, and brand loyalty require innovative solutions to balance affordability, taste, and perceived value.

Consumer perception of tortilla chips is shifting towards health-conscious and functional snacks. Rodriguez *et al*. (2025) reported that 47.2% of surveyed consumers preferred maize chips enriched with chia and flaxseed flour, while over 40% were willing to pay a premium for healthier, baked tortilla chips. Furthermore, innovations in sensory evaluation techniques, such as virtual reality (VR)-based taste testing (Man *et al*., 2025), have provided new insights into consumer preferences.

Conclusions

Nixtamalization remains a vital process in maize-based food production, enhancing nutritional value, functional properties, and safety. Technological advancements, including ecological nixtamalization and fortification, offer sustainable and health-promoting alternatives. The shift towards environmentally friendly nixtamalization techniques further aligns with global sustainability goals. Moreover, continuous research into processing improvements and ingredient innovations can help optimize product quality, reduce waste, and expand market potential. Future studies should focus on refining processing conditions, developing alternative alkalizing agents, and exploring consumer preferences to ensure widespread adoption of sustainable nixtamalization practices.

Table 1 : The effect of Nixtamalization on nutrient/component of food item

Nutrient/Component	**Effect of Nixtamalization**	**Sources**
Protein	Slight reduction due to heat but improved digestibility.	(Rolandelli *et al.*, 2024)
Amino Acids	Some essential amino acids may degrade slightly.	(Mendez *et al*. 2013).
Dietary Fiber	Increases due to changes in the grain's structure.	(Maya-Cortes *et al*. (2010
Calcium	Significantly increases due to lime (calcium hydroxide) absorption.	(Ochoa *et al.*, 2016)
Iron & Zinc	Bioavailability improves, but overall content may decrease slightly.	(Nieves-Hernandez *et al*., 2024).
Phytates	Reduced, leading to better mineral absorption.	(*Xu et al.*, 2010)
Antioxidants	Some loss occurs, but certain compounds become more bioavailable.	(*Xu et al.*, 2010)
Vitamins (B & E)	Partial degradation, especially of water-soluble vitamins.	(Rolandelli *et al.*, 2024).

Table 2 : The health benefits of nixtamalization

Health Benefit	**Explanation**
Improved bone health	Increased calcium absorption from lime treatment strengthens bones.
Better digestibility	Nixtamalization breaks down complex proteins, making them easier to digest.
Enhanced mineral absorption	Reduction in phytates improves iron and zinc bioavailability, preventing deficiencies.
Supports gut health	Increased dietary fiber promotes gut microbiota and digestion.
Reduced risk of neural tube defects	Higher folate retention supports fetal development during pregnancy.
Lower mycotoxin levels	The alkaline process neutralizes harmful mycotoxins, reducing toxicity risks.
Antioxidant benefits	While some antioxidants are lost, improved bioavailability supports cell protection.
Blood sugar regulation	Modified starch structure leads to a lower glycemic response, beneficial for diabetics.
Improved hydration & satiety	Changes in starch and fiber help retain water, increasing fullness and hydration.
Potential cardiovascular benefits	Increased fiber and minerals support heart health by reducing blood pressure risks.

Table 3 : The benefits of nixtamalization

Key Finding	Explanation	Source
Nixtamalization improves mineral bioavailability	Reduces phytates, enhancing calcium, iron, and zinc absorption.	(Xu *et al.*, 2010)
Enhances texture and flavor	Alters the structure, improving softness and taste.	(Santiago-Ramos 2018)
Partial loss of some nutrients	Some water-soluble vitamins and antioxidants degrade.	(Campechano Carrera *et al.*, 2012)
Increases dietary fiber	Structural modifications enhance fiber content.	(Maya-Cortes *et al*. 2010)
Reduces mycotoxins & contaminants	The alkaline process helps detoxify harmful substances.	(Pandey and Waghmare 2019).
Improves dough formation for masa	Alters starch and protein structure for better dough consistency.	(Rolandelli *et al.*, 2024).
Alters antioxidant activity	Some antioxidants are lost, but bioavailability improves.	(Mariscal *et al*., 2024)

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