Effect of thermal popping treatment on Toluqueño creole popcorn maize (*Zea mays* L. cv. Palomero Toluqueño): Changes in physical and structural properties

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ABSTRACT

Objective: To assess the effect of popping thermal treatment on the physical and structural properties of Toluqueño creole popcorn maize (*Zea mays* L. cv. Palomero Toluqueño)

Design/methodology/approach: Toluqueño creole maize and commercial used as a control, were subjected to three popping treatments: hot oil, hot air, and microwave. Popping yield, textural properties, and structural features were determined.

Results: The results showed that the treatment by hot air in commercial maize showed the highest pop yield (71.88%), while the microwave treatment was the best for Toluqueño maize (12.93%). The best textural characteristics for both types of maize were obtained after applying the hot air treatment, resulting in soft, low rubbing, and good chewing popcorns. The microstructural analysis on raw Toluqueño maize showed an intergranular space, which was related to a less compaction grade and consequently less hardness, meanwhile, the microwave popcorns showed the lowest gelatinization degree.

Limitations on study/implications: High resolution and improved methodologies to observe the starch grain and components distribution could have resulted in a better description of the effect of thermal treatment on the corn grains.

Findings/conclusions: Hot air treatment was the best process to obtain a good quality popcorn. The popping yield was related to humidity, hardness, grain shape, intergranular space, and the popping process.

Keywords: Popcorn maize (*Zea mays* L. cv. Palomero Toluqueño), expansion yield, textural properties, structural properties.

INTRODUCTION

Maize (*Zea mays* L.) is one of the most consumed cereals in the world. In Mexico, maize has a very important sociocultural value, and it is a basic food in the diet (Serna-Saldivar, 2021). There are several maize varieties, each one with distinctive genetic characteristics. Maize is used as a raw material to obtain flours, tortillas or snacks (popcorns) among other products. The morphological, botanical, and genetical features have been used as a guide to its classification. From this classification, it is possible to find the group of "indigenous varieties" named popping varieties in which the Toluqueño popcorn maize (*Zea mays* L. cv. Palomero Toluqueño) is included (Bautista-Ramírez *et al.*, 2020). This type of corn has smaller grains than other varieties. Also, it has specific composition and botanical unique features making it suitable to prepare popcorns (Sweley *et al.*, 2013).

The starch contained in the endosperm is moisten and it acquires a gelatinous consistency when heated, which is known as gelatinization (Wang *et al.*, 2017). During it heating process, the pericarp acts a barrier to contains the moisture, leading to a pressure accumulation up to the point of rupture and explosion of the grain (Sweley *et al.*, 2013). In the process, the water is evaporated, passing through of the protein matrix of the grain and intercellular spaces, reaching the required pressure to swell, expanding the grain, and blowing up (García-Pinilla *et al.*, 2021). The fast expansion of the grains in the surrounding air cools the starch, leading a spongy structure of low-weigh knows as popcorn (García-Pinilla *et al.*, 2021).

Two main factors have an important effect on the popping process to obtain good quality popcorns: moisture and pressure. The moisture content determines the quantity of grains that blown up as well as the expansion volume (Sweley *et al.*, 2013). According to Cañizares *et al.* (2020), the moisture content desirable to obtain an optimal volume of blown up is from 11.39 to 12.91%, when expanded without oil and it is between 10.21 and 11.73% when expanded using oil. Regarding to the pressure, there is a significant increase in the mean size of grain and expansion volume as the pressure is reduced inside of the grain (Quinn *et al.*, 2005). The physical and texture features of the corn grains could be the affected by the heat transference medium. In this sense, the most common ways to supply heat to prepare popcorns are microwave, hot air, and immersion in hot oil. Each one of these methods result in different textural and microstructural features in the popcorn. Nowadays, through microscopy and image analysis is possible to describe and evaluate the structure of grains (Rojas-Candelas *et al.*, 2022) and the obtained products such as popcorns (García-Pinilla *et al.*, 2021).

Bautista-Ramírez *et al.* (2018), after studying the geographical distribution of the Palomero Toluqueño maize, pointed out that the local producers decided not to continue the production of this crop so, this breed could disappear if a feasible strategy is not implemented to encourage its conservation and use. As the Palomero Toluqueño is a popping corn, it is important to evaluate its popping yielding as well as its expansion volume (formation and size of the popcorn) to determine if it can compete with commercial brands. At our best knowledge, there are not studies about applying different thermal process to obtain information that may contribute to alternative uses to preserve this local variety. In this sense, the objective of this work was to assess the effect of thermal treatment on the physical and microstructural properties of commercial and Toluqueño popcorn maize (*Zea mays* L. cv. Palomero Toluqueño).

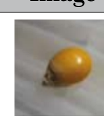
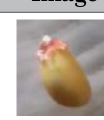
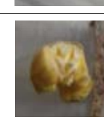
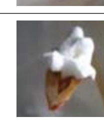
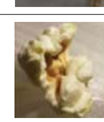
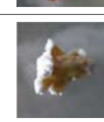
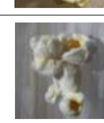
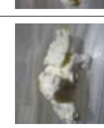
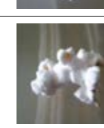
MATERIALS AND METHODS

Area and sample collection: Popcorn maize Toluqueño (TM) was grown and collected in the winter of 2018 in San Marcos Tlazalpan, Morelos, State of Mexico. The commercial maize (CM) was purchased in a local market. The vegetable oil used for the popping process was 1,2,3 brand (La Corona, S. A de C. V.).

Preparation of popcorns. Three methods were used to prepare popcorns with the two types of maize: microwave (MW), hot oil (HO), and hot air (HA). A borosilicate glass container (Ecolution EKPRE-4215, International Inc., Florida, USA) was used to prepare popcorn by microwaves (Hamilton Beach Brands Holding Company, model HB-P70J17AL-V2C, Virginia, USA). To prepare popcorns by hot oil, a popcorn maker machine (Hamilton Beach model 73302, Hamilton Beach Brands Holding Company, Virginia, USA) was used. Popcorns by hot air were prepared using a popcorn maker machine (Hamilton Beach model 73400, Hamilton Beach Brands Holding Company, Virginia, USA). For all treatments, 26 grams (equivalent to 140-176 maize grains) of Toluqueño or commercial maize samples were used to prepare popcorns. The temperature during popping was measured using a thermocouple TM500 (Extech Instruments, Massachusetts, USA). The temperature was registered each 30 seconds until 2.5 minutes.

Popping yield. The popping yield was measured after 1 and 2 minutes of the respective thermal treatment. The popcorns obtained were grouped according to similar shape and size. Four categories were used, using numbers of 0, 1, 2, 3, and 4. The zero category was for the grain without popping, 1 and 2 were for intermedium popping, and 3 and 4 to describe the popcorns with desirable features (higher volume and complete popping). This classification is based on the different popcorn shapes produced on the popping process and is based on the degree of opening of the grain. Figure 1 shows the different categories assigned to commercial and Toluqueño maize.

Figure 1. Categories assigned to commercial and Toluqueño maize.

Category	Description	Image	Image
0	Maize grains without popping.		
1	Popcorn grains fractured, leading to observe a small part of starch. They are hard and small.		
2	Maize grains not completely popping, less had than category 1, but more starch exposed.		
3	A crispy popcorn maize, acceptable size for consumers.		
4	A popcorn with the starch completely exposed, soft, fragile, the highest size respect to the other categories.		

Morphometric characteristics. The size (perimeter and area) of raw and popped corn were measured by image analysis using the Image J program (National Institutes of Health, Bethesda, MD, USA). Images of samples were obtained using a digital camera from a smartphone Galaxy M31 with a camera of 64 megapixels (Samsung Electronics, Suwon, South Korea). Then the images were converted in black and white images for further analysis.

Moisture content. The moisture content in raw and popped corn was determined using a thermobalance (Moisture Analyzer MB21; Ohaus Corp, Pine Brook, NJ, USA.) following the pre-established program of drying at 130 °C for 10 minutes. For all measurements, the samples were grounded in a coffee grinder (KitchenAid BCG111OB; Whirlpool Corporation, Benton Harbor, USA).

Heating rate kinetic. The temperature during the different thermal treatments for both maize samples was measured using a 12-channel Thermocouple Data Recorder Model TM500 (Extech Instruments, Massachusetts, USA). Measurements were carried out since the 00:00 minute progressing every 30 seconds up to 2.5 minutes.

Determination of texture parameters. The texture analysis was performed in a texture analyzer (TA-XT plus; Stable Micro Systems, Godalming, Surrey, UK). A cylindrical probe (stainless steel SMS P/2 of 2 mm) was used to determine the textural parameters in raw corn. The hardness was measured using a compression test, penetrating 25% of depth at a crosshead speed of 7 mm/s. Each grain measured individually on the maximum diameter and always in the same way for all grains.

For the popcorn samples, a TPA test of double compression was carried out using an aluminum compression probe of 75 mm (SMS P/75) to compress 50% of the initial height at a crosshead speed of 2 mm/s. Individual popcorn were analyzed. In all cases, the parameters obtained were hardness, fractureability, elasticity, cohesiveness, gumminess, chewiness, and resilience.

Color. The color of all samples was determined using a colorimeter (Konica Minolta CR-400/410, New Jersey, USA). CIELab scale was used to evaluate color.

Microstructure analysis. The microstructural analysis allowed observing the structure of Toluqueño and commercial popcorn maize. The analysis was performed in a stereoscope (Carl Zeiss, Oberkochen, Baden-Wurtemberg, Germany). Central parts of grains were cut, and cross sections were obtained using a scalpel. The samples were stained with lugol to observe the starch granules at 10x and 40x.

Statistical analysis. All measurements were carried out in triplicate and quantitative data are presented as mean ± standard deviation. The data were statistically treated by ANOVA and the Tukey test (SigmaPlot V.11.0. Systat Software Inc, San Jose, CA, USA). $p \leq 0.05$ values were considered significantly different.

RESULTS AN DISCUSION

Figure 2 shows the popping yield for commercial maize (CM) after 1 and 2 minutes of the three methods of preparation (hot air (HA), hot oil (HO), and microwave (MW)). One minute was insufficient to pop as the heat transfer was low, resulting in a poor popping yield (in all cases, lower than 3.8%). MW was the most effective (3.8%) because the high energy

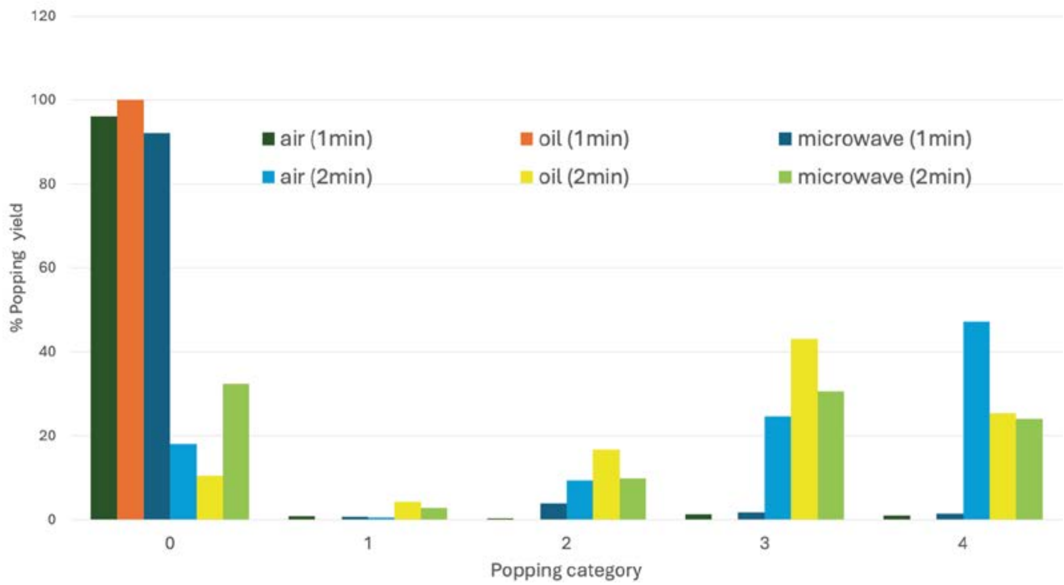


Figure 2. Popping yield for commercial maize after 1 and 2 minutes of treatments.

emitted by microwave radiation promotes the vibration of water molecules resulting in a rapid gelatinization of starch and popping. In the method by HO it is inferred that it takes energy to heat the oil (heat transfer medium) before starting the popping process, then it is the less effective method. The results for treatment of 2 minutes were surprisingly different. The HO and HA treatments showed more than 40% of grains popped in the 3 or 4 levels (Figure 1). Specifically, HA showed the highest popping yield in 3 and 4 levels (71.88%), while HO showed 68.56% and only 54.14% for MW.

HA reached the highest temperature in a short time and the air is in direct contact with the grains. When oil is the heat transmitter, it takes more time to reach the optimum temperature for popping. In the case of MW, the heat affects individually the grains. Koutchma (2022) reported that variations in electrical conductivity in microwaves causes non-uniform internal heating. Also, it is probably that, as the high microwave energy penetrates the grains, part of the moisture evaporates during the popping process resulting in an incomplete popping. The mechanism of heat transfer is different in all treatments. In the process by hot air both conduction and convection phenomena are involved. In the case of hot oil, convection drives the process (Rani *et al.*, 2023); while radiation is involved in the MW popping process.

Figure 3 shows the popping yield for Toluqueño creole maize (TM) after treatment for 1 and 2 minutes in the three preparation methods. No popping was registered after 1 minute in all treatments. Considering that levels 3 and 4 are the optimum, MW and HA treatments showed the best popping yield with 12.93% and 11.96%, respectively. In HO treatment only 5.68% of the grains reached the optimum levels for consumption.

Results showed that the popping yield in TM was almost six times lower compared to CM, regardless of the treatment used for popping. These differences are attributed to their genetical characteristics. Also, it is possible that genetic improvements have been

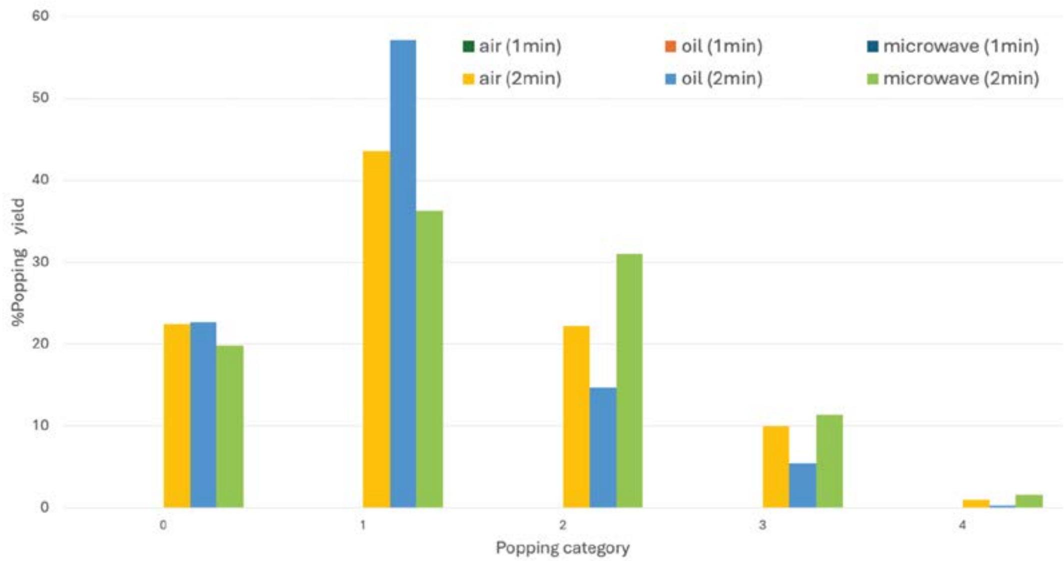


Figure 3. Popping yield for Toluqueño creole popcorn maize after treatment for 1 and 2 minutes.

implemented in commercial varieties to obtain the best popping yield characteristics (Divya, 2024).

Table 1 shows the size characteristics (area, perimeter) for the different categories of CM and TM. It is possible to observe that the area as perimeter is higher in TM.

The higher size in TM could explain its lower popping rate, because more energy is required to pop this variety. Also, the grain form may contribute to popping, thus CM was the most likely to pop because a more uniform heat transfer could be expected due to its more round form.

Table 2. Shows the total area in 100g of CM and TM popcorns for the different thermal treatments. The total area in CM was higher in all cases, but the treatment with HA for CM presented the highest among treatments. In the case of TM, the HA and MW treatments presented higher values compared to the HO treatment.

Moisture content in maize grains influences directly the quality of popcorns, because it affects the popping (García-Pinilla *et al.*, 2021). In this work, CM presented a higher moisture content (10.61±1.04%) than TM (8.42±0.29%), which is related to the popping.

Table 1. Size characteristics (area, perimeter) for category of popping in commercial and Toluqueño maizes.

Category	Commercial maize		Toluqueño maize	
	area (cm^2)	perimeter (cm)	area (cm^2)	perimeter (cm)
0	0.27 ± 0.03^{a}	1.94 ± 0.17^{a}	0.70 ± 0.04^{a}	3.52 ± 0.20^{a}
1	0.49 ± 0.06^{b}	2.66 ± 0.18^{b}	0.91 ± 0.04^{b}	4.30 ± 0.19^{b}
2	1.34 ± 0.08^{c}	5.31 ± 0.15^{c}	1.22 ± 0.04^{c}	4.47 ± 0.17^{b}
3	1.99 ± 0.28^{d}	6.98 ± 0.35^{d}	2.61 ± 0.11^{d}	8.12 ± 0.14^{c}
4	3.22 ± 0.46^{e}	9.47 ± 0.31^{e}	4.58 ± 0.33^{e}	11.02 ± 0.70^{d}

* Results are presented as means±SD (n=3).
** Values with different letters in the same column indicate significant difference ($p \leq 0.05$).

Table 2. Total area in 100g of popcorn commercial and Toluqueño maize.

Category	Commercial maize			Toluqueño maize		
	oil (cm^2)	air (cm^2)	microwave (cm^2)	oil (cm^2)	air (cm^2)	microwave (cm^2)
0	2.81±0.32[a]	4.87±0.32[a]	8.76±0.32[a]	15.94±1.00[a]	15.75±0.99[a]	13.92±0.87[a]
1	2.07±0.23[b]	0.34±0.23[b]	1.41±0.23[b]	52.06±2.37[b]	39.69±1.81[b]	33.10±1.51b
2	22.42±1.29[c]	12.53±1.29[c]	13.25±1.29[c]	17.85±0.53[c]	27.05±0.81[c]	37.85±1.13[c]
3	85.71±12.28[d]	48.93±12.28[d]	60.70±12.28[d]	14.15±0.58[d]	25.88±1.06[d]	29.54±1.21[d]
4	81.85±11.28[d]	152.12±11.28[e]	77.73±11.28[e]	1.15±0.08[e]	9.31±0.66[e]	7.34±0.52[e]
Total area	194.87±18.71[a]	218.79±18.71[b]	161.85±18.71[c]	101.14±4.57[d]	117.68±5.33[e]	121.75±5.25[e]

* Results are presented as means±SD (n=3).
** Values with different letters in the same column indicate significant difference ($p \leq 0.05$).
*** Values of total area with different letters in the same line indicate significant difference ($p \leq 0.05$).

As moisture content increases, optimum popping conditions are reached. In this sense, the optimum moisture content to obtain the maximum popping volume is around 12%. A lower moisture content will result in an insufficient vapor pression during heating and the popping will not take place. High moisture content will result in a collapse of the pericarp at a lower vapor pressure than required for the popping to occur (Sweley *et al.*, 2013). As TM had a low moisture content compared to CM, a less popping yield was reached.

Table 3 shows the moisture content for the different treatments for CM and TM. There is a general trend to increase the category of popping when the moisture content is lower.

In TM there is a decrease of moisture content in the category 4 for the oil treatment, but no significant differences were observed in the other treatments. These results are related to the area values of popcorn, because in CM there is a major expansion with respect to its initial size, while the total area reached in TM was lower. Then, it can be inferred that as the exposed area increases, there is a higher loss of moisture immediately after popping. On the other hand, in general, the moisture content in samples treated with oil was lower compared to the other treatments in both varieties which could be attributed to two phenomena: a) the continuous evaporation of water due to the heat transfer and, b) the decreasing evaporation driven by the diffusion of water from the internal structure to the surface of the grain.

Table 3. Moisture content (g/100g) of commercial and Toluqueño maize grains.

Category	Commercial maize			Toluqueño maize		
	oil	air	microwave	oil	air	microwave
0	4.51±0.08[a]	7.06±0.25[a]	7.00±0.04[a]	3.64±0.23[a]	5.51±0.80[a]	5.60±0.26[a]
1	3.80±0.06[b]	7.70±0.10[b]	6.36±0.04[b]	3.11±0.18[b]	4.86±0.16[a]	4.69±0.08[b]
2	2.42±0.03[c]	5.38±0.13[c]	6.07±0.56[c]	3.30±0.09[c]	5.54±0.09[a]	5.20±0.25[c]
3	2.59±0.11[d]	5.59±0.07[d]	5.13±0.44[d]	3.53±0.04[d]	6.68±0.23[b]	5.34±0.11[a]
4	3.27±0.10[d]	4.65±0.18[e]	4.74±0.46[e]	2.91±0.08[e]	5.60±0.14[a]	5.76±0.16[a]

* Results are presented as means±SD (n=3).
** Values with different letters in the same column indicate significant difference ($p \leq 0.05$).

Figures 4 shows the heating kinetic for the three treatments (HO, HA and MW) for both maize varieties. HA reached the highest temperatures in less time (heating rate) compared to HO and MW treatments. In the first minute, CM reached 182 °C (2.136 °C/s), while TM had 143.8 °C (2.02 °C/s). The differences in heating rate can be explained by the grain geometry, since the higher area of TM reduced the air circulation power and the heat transfer.

In MW, the heating rate was 0.815 and 1.163 °C/s for CM and TM, respectively which could explain the higher popping yield for TM. According to Proctor (2018), although the microwaves penetrate evenly throughout the product, the distribution of the electric field is not even throughout the irradiated material. Thus, the energy is not dispersed homogeneously since the distribution of the electrical field will depend on the geometry and the dielectric properties of the food. Apparently, the geometry of the maize grain induces a better behavior in microwave heating.

In HO for CM the heating rate was 0.27 °C/s, while for TM was 0.53 °C/s. Both are lower than the others because the oil must be heated first taking a longer time compared to HA and MW. Also, this explains the low rates of popping obtained with HO. The temperature of the heating medium is one of the important factors for the quality of popcorn, as it plays an essential role in the popping process. The temperature, area, and geometry of heating also play an important role in the popping of maize. Reaching high temperature in a short time will result in fewer grains without popping (Subramani *et al.*, 2023).

The texture analysis of the raw grains showed that CM is harder (319.176±60.203 N) than TM (234.997±27.97 N). According to Gao *et al.* (2024), the hardness of maize grain is related to the floury endosperm (soft) and glassy (hardness), which depends on size, morphology, compaction degree of the starch granules, and the proteinic matrix. These parameters could explain the popping yield observed in TM, since it is less hard, its pericarp is soft, and the intern pressure in the grain during cooking is low resulting in a low level of popping. Also, it is inferred that there is a less compaction of starch granules and high quantity of floury endosperm contributing to a low popping yield.

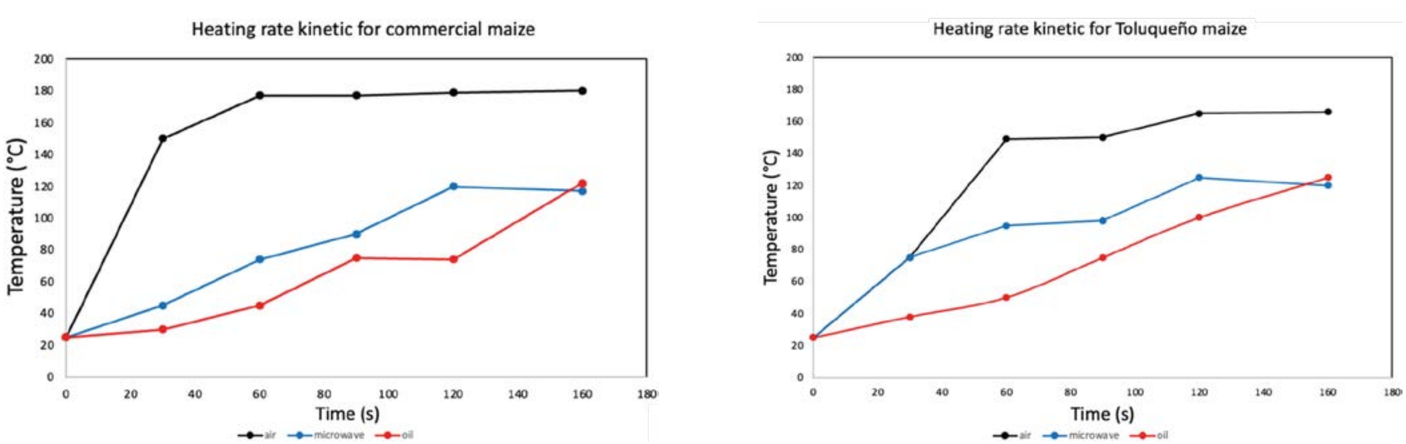


Figure 4. Heating rate kinetic for commercial maize and Toluqueño maize.

Table 4 shows the results for the texture analysis for both varieties of popcorns. The hardness of TM prepared with HO (273.658±87.469 N) and MW (283.975±79.021 N) treatments was higher compared to the HA treatment (184.121±73.889 N). Similar behavior was observed for CM; however, the values were low for all its treatments compared to TM. Results indicate that CM popcorns are softer and have a better texture. It seems like HA promoted a fast popping of maize grains promoting the release of starch which could explain their lower hardness. On the other hand, popcorns prepared with HO suggest that oil affects positively the texture, since it is smoother compared to those obtained by MW process.

Fracturability results show that CM popcorns are more brittle compared to TM. CM with HA required less force to break up (8.60±6.10), while TM by microwave was harder to break up (34.80±13.10). The elasticity results showed the highest value (0.33±0.038) in TM with HO treatment and it was significantly different to elasticity of CM. These values obtained after HA and MW treatments of CM and TM samples were no significantly different. The cohesiveness values were low, but the treatment with HA did not show significant differences in CM and TM. The highest values of gumminess obtained for popcorn were observed in TM prepared under HO (98.22±54.71) and HA (57.0±32.98), while that the lowest value was found in the MW treatment (10.17±4.13). In CM, the lowest value obtained was observed in HA (14.25±6.83), while no significant differences was found between HO and MW treatments. Chewiness values of popcorns from TM prepared with HO and HA indicate that a higher force is needed to disintegrate than that of MW. Texture analysis is of great importance to determine the acceptability and quality of foods. According to Sweley *et al.* (2013), the most desirable texture parameters in maize popcorns are associated with soft and crispy characteristics. Those described as

Table 4. Texture analysis of popping maize (category 4).

Texture parameter	Maize variety	Thermal treatment		
		Oil	Air	Microwave
Hardness (N)	CM	103.90 ± 41.20^{a}	62.10 ± 25.40^{a}	112.05 ± 0.05^{a}
	TM	273.70 ± 87.50^{b}	184.10 ± 73.9^{b}	284.1 ± 79.00^{b}
Fracturability (N)	CM	17.20 ± 5.40^{a}	8.60 ± 6.10^{a}	15.35 ± 11.9^{a}
	TM	21.40 ± 4.60^{a}	13.80 ± 1.60^{a}	34.80 ± 13.10^{b}
Elasticity	CM	0.28 ± 0.04^{a}	0.21 ± 0.05^{a}	0.23 ± 0.032^{a}
	TM	0.33 ± 0.03^{b}	0.22 ± 0.05^{a}	0.23 ± 0.05^{a}
Cohesiveness	CM	0.28 ± 0.03^{a}	0.23 ± 0.03^{a}	0.26 ± 0.02^{a}
	TM	0.34 ± 0.09^{a}	0.29 ± 0.06^{a}	0.35 ± 0.01^{b}
Gumminess	CM	29.79 ± 15.58^{a}	14.25 ± 6.83^{a}	29.36 ± 9.16^{a}
	TM	98.22 ± 54.71^{b}	57.01 ± 32.98^{b}	10.17 ± 4.13^{b}
Chewiness	CM	8.57 ± 5.23^{a}	3.19 ± 2.26^{a}	6.60 ± 2.29^{a}
	TM	31.29 ± 16.03^{b}	13.40 ± 9.68^{b}	2.45±1.27b
Resilience	CM	0.11 ± 0.02^{a}	0.85 ± 0.01^{a}	0.11 ± 0.01^{a}
	TM	0.19 ± 0.06^{b}	0.15 ± 0.04^{b}	0.19 ± 0.04^{b}

* CM: commercial maize; TM: Toluqueño maize.

** Values with different letters in the same column per texture parameter indicate significant difference ($p\leq0.05$).

undesirable characteristics need to be chewed for longer and tend to stick to the teeth. Therefore, TM popcorns produced by HA had the most desirable characteristics.

Table 5 shows the color values for raw maize and those after three different thermal treatments. The L value for raw CM (58.95±1.58) was lower compared to TM (64.81±1.83). Positive b* values indicate a yellow color. In this way, CM had a higher value (28.01±0.12) compared to TM (26.20±1.49). The statistical analysis indicated a significant difference in the b* value of raw maize samples. In the CIELab scale, a* value in raw materials refers the red color. CM had a significantly more intense red color (7.72±0.10) that TM (6.03±1.07). In general, L values were higher after the thermal treatments because of an increased lightness. Popcorns prepared with HO showed the lowest L values with a significant difference between other samples. The possible reason explaining these results is the remaining oil in the samples. A significant decrease in a* y b* values was observed in the popcorns obtained by CM and TM. As mentioned before, those values correspond to yellow and red color. The color is mainly due to carotenoids presents in samples and, when it was exposed to thermal treatments, oxidation processes were promoted. However, a drastic decrease in b* value was observed in TM indicating that the pigments in this grain are more susceptible to thermal treatments.

Differences in size, form, pericarp thickness, endosperm distribution, and degree of compaction are observed in Figure 5. The differences between grains have an important effect on their behavior during popping by the different methods, in addition to their physical and chemical characteristics. The pericarp thickness of CM was higher compared to TM. This is in line with the findings of Bautista-Ramírez *et al.* (2019), who evaluated the thickness of the pericarp of CM and TM reporting values of 0.54 μm and 0.9 μm, respectively.

Figure 6 shows the microstructure of popping maize (category 1 and 4) for CM and TM. Is possible to observe that it is A notably higher number of starch granules with defined shape was observed in the category 1 of both types of maize for the three heating treatments indicating a smaller gelatinization degree during the popping process. Furthermore, greater intergranular space is noticed in TM, which may be related to a low compacting degree which could be associated with lower values of hardness in the grain without popping (Table 4). For category 4, a higher expansion degree was observed in starch granules after HA and MW treatments although they kept well-defined structures. HO treatment showed a major gelatinization evidenced for larger starch granules. TM

Table 5. Color parameters for commercial and Toluqueño maize grains.

System CIE	Raw maize		Popping grains					
	CM*	TM*	Commercial maize **			Toluqueño maize**		
			oil	air	microwave	oil	air	microwave
L	58.95±1.58[a]	64.81±0.08[b]	96.10±5.49[a]	99.56±8.65[h]	100±2.33[v]	89.76±2.82[b]	97.97±11.21[h]	95.99±2.26[w]
a*	7.72±0.10[a]	6.03±0.06[b]	1.46±0.52[a]	1.46±1.00[i]	1.21±0.19[x]	0.91±0.98[a]	1.45±0.56[i]	1.51±0.31[x]
b*	28.01±0.12[a]	26.20±0.03[b]	25.98±2.14[a]	25.89±0.70[j]	23.00±3.08[y]	10.37±2.07[b]	8.43±1.16[k]	8.38±1.81[z]

* Values with different letters in the same file (per maize type) indicate significant difference ($p \leq 0.05$).
** Values with different letters in the same file per treatment (oil, air, microwave) indicate significant difference ($p \leq 0.05$).

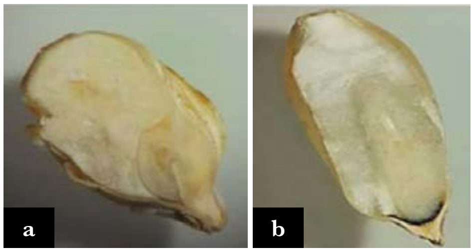


Figure 5. Microstructure from a) commercial maize and b) Toluqueño maize.

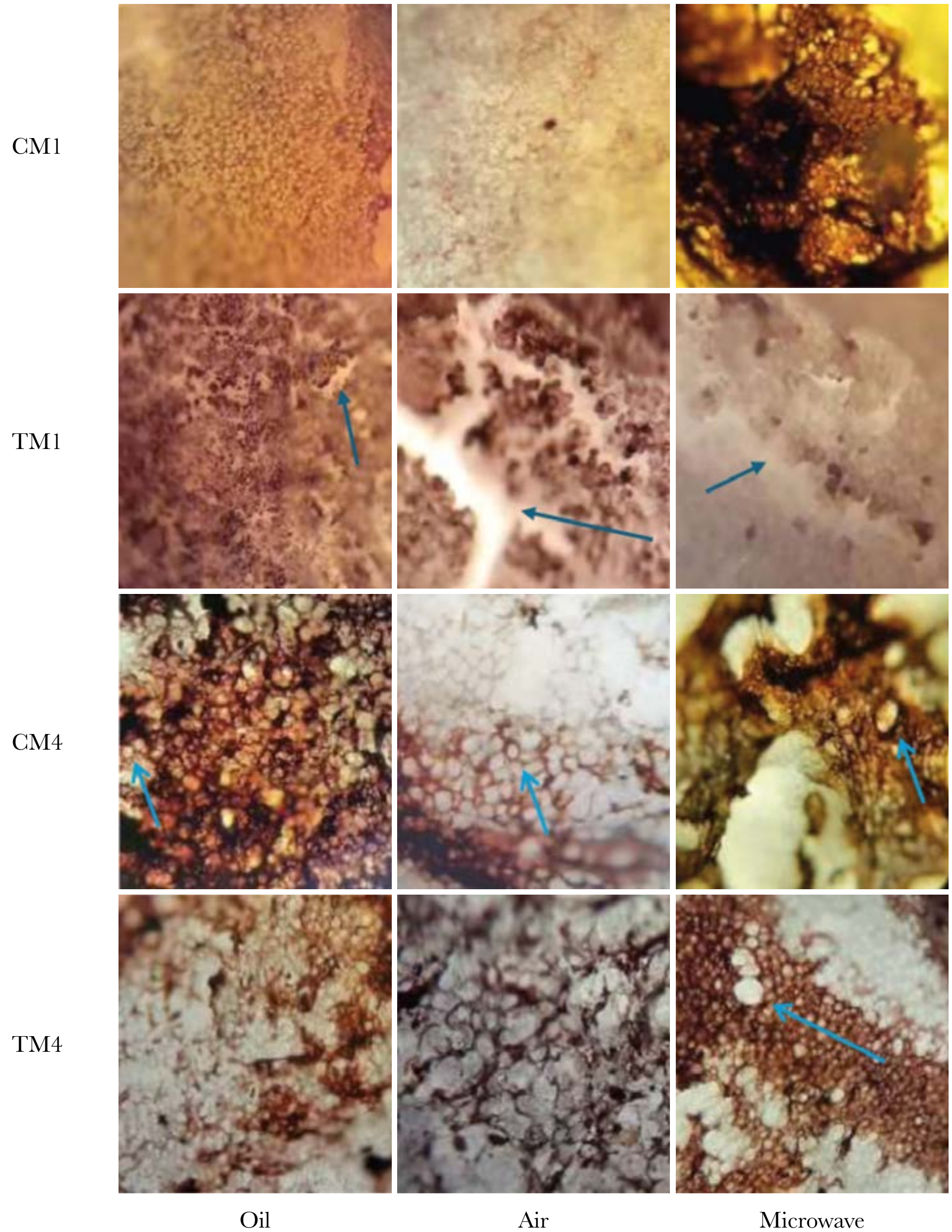


Figure 6. Microstructure of commercial and Toluqueño maize grains.

showed a notable swelling and deformation of the granule after treatment with HO and HA opposite to the behavior observed in the MW treatment suggesting a lower degree of gelatinization. These results can be explained by the higher hardness values observed in popcorn obtained after microwave treatment. To confirm the degree of gelatinization it is recommended to carry out further analyses regarding this parameter.

CONCLUSIONS

Results showed that TM had a lower popping yield compared to CM irrespective of the heating method which is related to its larger size, lower moisture content, and grain hardness. The HA method allowed obtaining the best results for popping yield and texture of popcorns in both types of maize grains; however, TM have a lower quality than those prepared from CM. Microstructure analysis allowed observing different intergranular spaces and degrees of gelatinization; nevertheless, more studies are needed to conclude on this. This study provides important information regarding the behavior of the TM after different thermal treatments.

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