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Popcorn from native maize with normal endosperm produced using a cannon puffing machine

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Abstract

Maize is the most widely produced cereal in the world and is the basis for many processed products, including snacks and breakfast cereals. One of the main technologies used to process whole grains is the cannon puffing machine; however, its application in maize popping has been scarcely studied. The objective of this study was to evaluate the puffed quality of native maize varieties with different endosperm hardness levels using a cannon puffing machine, to validate the performance of a semi-industrial device. Native popping maize and maize with normal endosperm were evaluated under different processing conditions. Expansion volume (EV), percentage of unpuffed (UPK) and partially puffed kernels, expansion shape, moisture content, and grain hardness were determined. The best processing conditions were achieved using grains without moisture conditioning and an operating pressure of 1.03 MPa in the cannon puffing machine. Under these conditions, no unpuffed kernels (UPK) were observed, and an average EV of $11.8 \text{ cm}^3 \cdot \text{g}^{-1}$ was obtained, with a mushroom shape and low moisture content. Puffed maize is a healthy snack alternative that adds value to native maize varieties, regardless of their endosperm hardness.

► **Keywords:** shape of puffed maize, floatation index, operating pressure, expansion volume.

Introduction

Maize is the most widely produced cereal in the world and is the basis for a wide variety of food products. In Mexico, approximately 600 food and beverage items made from maize have been reported (Pérez-Ruiz et al., 2024). In the snack and breakfast cereal industries, maize plays a key role as the primary raw material (Fast et al., 2020; Serna-Saldívar & Chuck-Hernandez, 2019). One of the most used technologies for processing maize in these industries is extrusion, which involves a mixture of corn grits with water (15-18 %) and various flavoring ingredients. This mixture is passed through an extruder, where it is subjected to high pressure and short residence times (Sharifi et al., 2021).

An alternative method for processing maize kernels is the use of a cannon puffing machine (Lee et al., 2019), which allows for the processing of whole grains such as rice, wheat, barley, and oats. In this method, grains are first conditioned to a moisture content between 13 and 15 % (Lee et al., 2019; Mariotti et al., 2006) and then introduced into the cannon chamber, where they are heated and subjected to pressures ranging from 0.5 to 1.5 MPa (Jia et al., 2021; Lee et al., 2019). Subsequently, the sudden release of the chamber causes rapid decompression, which leads to grain expansion.

The principle behind this technology lies in the generation of superheated steam within the grain, where the pericarp acts as a micro-pressure chamber that traps the vapor.

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Intense heating induces a glass transition in the grain matrix, making it more extensible and allowing internal diffusion of the vapor. Upon the opening of the expansion chamber, the steam escapes abruptly, expanding the grain and forming a new internal structure (Mounir et al., 2023).

The use of a puffing cannon machine for maize processing has received limited attention in scientific literature. Although studies by Mrad et al. (2014) and Rajha et al. (2021) have examined Peruvian maize, they do not provide information on grain characteristics. Therefore, the aim of this study was to assess the puffed quality of native maize varieties with varying endosperm hardness using a puffing cannon machine to validate the performance of a semi-industrial device developed by the Centro Nacional de Estandarización de Maquinaria Agrícola, at the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP), Mexico.

Materials and methods

A total of three experiments were conducted to identify the optimal conditions for processing maize using a lab-scale cannon puffing machine (JCK-Baomihua, JVSUFUIK, China). In the first experiment, three landrace maize (Palomero Toluqueño, Chapalote, and Arrocillo) were used. These landraces are known for their high kernel hardness and their ability to pop using traditional methods such as pan, microwave, and hot air. Two moisture levels (13 and 14 %) were tested, based on previous reports indicating that these conditions are optimal for achieving higher expansion volumes (Sweley et al., 2013). The operating pressure in the cannon puffing machine was set at 0.98 MPa (Jia et al., 2021).

The second experiment aimed to determine whether puffed maize could be produced from varieties with lower

endosperm hardness. Therefore, native maize samples were selected and classified into three categories based on endosperm hardness: hard (H), intermediate (I), and soft (S). All samples were conditioned to 14 % moisture content (the optimal level identified in the first experiment) and processed at 0.98 MPa using the cannon puffing machine. In the third experiment, unconditioned maize samples with moisture contents between 11 and 13 % were used, and the operating pressure was increased to 1.18 MPa. Maize types included hard (H), intermediate (I), soft (S), and very soft (VS) endosperm categories. Maize conditioned to 14 % moisture was not used in this experiment, as it was observed that, under this pressure, the grains lost their mushroom shape and instead developed a butterfly-like form (Figure 1).

In all three experiments, a lab-scale cannon puffing machine with an 80 mL capacity was used. Each sample consisted of 70 g. Once the processing conditions were identified in the laboratory, they were scaled up to a semi-industrial cannon puffing machine. (Figure 2). At this stage, native maize samples without moisture conditioning were processed at a pressure of 1.03 MPa (Oscoco-Quispe, 2013), using a sample size of 1 kg. All measurements in both the lab-scale and semi-industrial cannon puffing machines were performed in duplicate.

Grain characterization and puffed quality

Moisture content (MC), flotation index (FI), and 100-kernel weight (HKW) were determined in the grains (Vázquez-Carrillo et al., 2023). Regarding FI, values from 0 to 12 correspond to very hard maize grains, 13 to 37 to hard maize grains, 38 to 62 to intermediate maize grains, 63 to 87 to soft maize grains, and >88 to very soft maize grains. Meanwhile, HKW values greater than 38 g indicate large maize grains, 33 to 38 g medium maize grains, and less

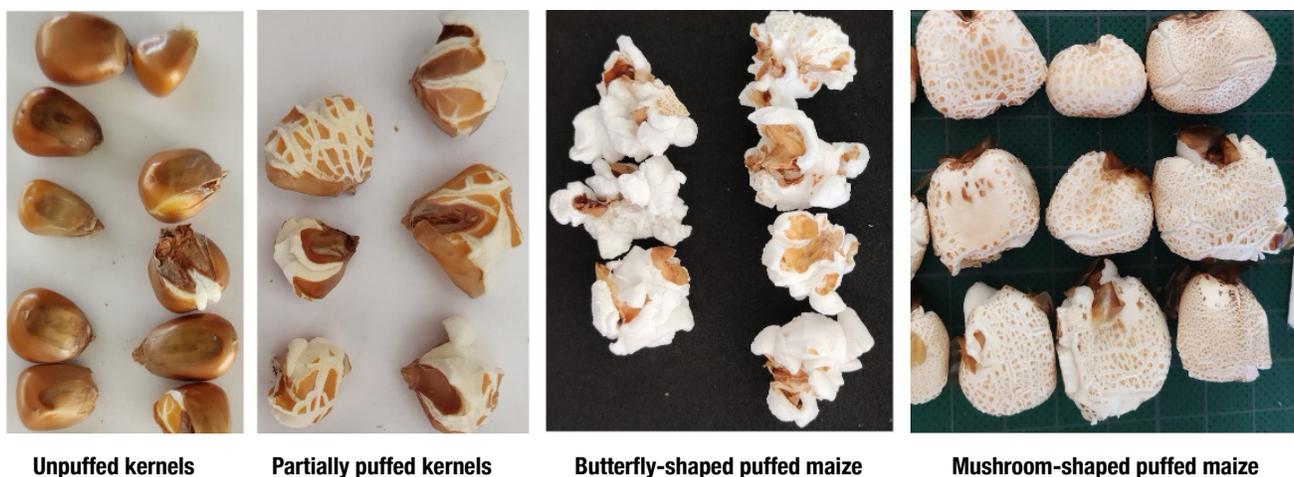


Figure 1. Shapes of normal-endosperm maize kernels obtained through processing with a cannon puffing machine.

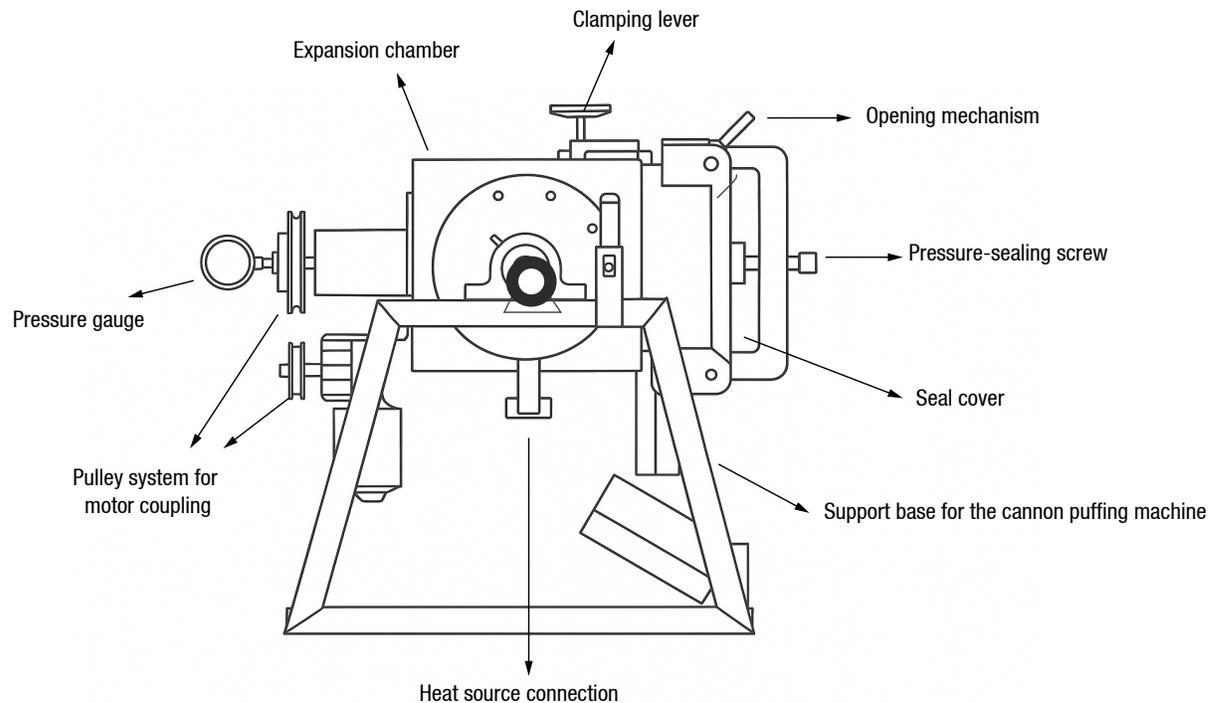


Figure 2. Diagram of the cannon puffing machine manufactured by the *Centro Nacional de Estandarización de Maquinaria Agrícola*.

than 33 g small maize grains. To evaluate puffed quality, expansion volume (EV; $\text{cm}^3 \cdot \text{g}^{-1}$) was estimated based on the total volume of puffed kernels in a 1000 mL measuring cylinder (García-Pinilla et al., 2019). Additionally, unpuffed kernels (UPK) and partially puffed kernels (PPK) were counted (Figure 1) to calculate their percentages (Sweley et al., 2013). The expanded kernels were separated according to their shape (mushroom or butterfly), and their percentages were estimated. The moisture content of the puffed maize was determined using method 44-15.02 of the American Association of Cereal Chemists (AACC, 2020). To evaluate texture, 10 kernels were randomly selected and analyzed using a texture analyzer (model CT3, Brookfield, USA) with a 25.4 mm diameter spherical probe. The test speed was $1 \text{ mm} \cdot \text{s}^{-1}$, and the target deformation was 10 mm. Results were expressed in Newtons (N).

Data analysis

In experiment one, a factorial design nested within a completely randomized design was used, with two sources of variation: genotype (three levels) and conditioning moisture (two levels). In the subsequent experiments, a completely randomized design with a single factor (genotype) was implemented. In all cases, an ANOVA was performed, followed by Tukey's multiple comparison test at a 5 % significance level. Data was analyzed using the SAS software (SAS Institute Inc., 2002).

Results and discussion

Native popping maize

The Palomero Toluqueño, Arrocillo, and Chapalote landraces are ancient indigenous maize known for their ability to pop (Wellhausen et al., 1951). However, this trait has been gradually lost as their germplasm mixed with other types of maize (Bautista-Ramírez et al., 2020). These varieties are also at risk of extinction due to their low productivity (Gámez-Vázquez et al., 2014).

The analysis of the genotype factor showed that processing with a cannon puffing machine produced higher expansion volumes (Table 1) than previously reported for grains of the same landraces (Bautista-Ramírez et al., 2020; Vázquez-Carrillo et al., 2019), with low percentages of unpuffed kernels and a predominance of the butterfly shape. Final moisture values were similar to those reported for popcorn processed by microwave or hot air methods (Ranathunga et al., 2016). Significant differences ($p < 0.05$) observed in the puffed quality variables can be attributed to the inherent characteristics of each landrace, although factors such as soil conditions, harvest and postharvest practices, and grain composition also play a role (Sweley et al., 2013).

Conditioning moisture had a significant effect ($p < 0.05$) on VE, UPK, and the moisture content of the product.

Table 1. Comparison of mean values for puffed quality variables in conditioned native maize processed with a cannon puffing machine.

| Genotype | EV (cm ³ ·g ⁻¹) | UPK (%) | MS (%) | BS (%) | Moisture (%) |
|---------------------|--|---------|---------|---------|--------------|
| Toluqueño | 19.45 b | 2.85 b | 8.64 c | 79.6 a | 2.97 b |
| Arrocillo | 21.14 a | 0.36 b | 26.86 a | 69.5 b | 5.07 a |
| Chapalote | 17.43 c | 19.44 a | 18.13 b | 57.2 c | 5.0 a |
| HSD | 1.35 | 2.9 | 7.73 | 8.36 | 0.32 |
| Conditioning | | | | | |
| 13 % | 18.56 b | 9.26 a | 17.09 a | 68.98 a | 4.55 a |
| 14 % | 20.12 a | 5.83 b | 18.66 a | 68.6 a | 4.15 b |
| HSD | 0.878 | 1.89 | 5.04 | 5.44 | 0.21 |

EV: expansion volume; UPK: unpuffed kernels; MS: mushroom shape; BS: butterfly shape; HSD: honestly significant difference. Different letters within each column and each source of variation indicate significant differences (Tukey, $p < 0.05$).

An initial kernel moisture of 14 % resulted in the highest VE, as well as the lowest UPK and moisture content in the puffed kernels (Table 1). Several studies with popcorn maize hybrids have reported that conditioning moisture is a critical factor for achieving optimal popping characteristics (high VE and low UPK), as moisture levels below 12 % or above 15 % reduce VE (Cañizares et al., 2024; Gökmen, 2004). Additionally, this parameter also affects the shape of the puffed kernel (García-Pinilla et al., 2019).

Furthermore, it was demonstrated that maize with very hard endosperm (VH, FI 0 to 9 %) can also be puffed using a cannon puffing machine. The best results, in terms of higher VE and fewer UPK, were achieved at 14 % conditioning moisture. Consequently, this condition was applied in the second experiment.

Native maize with different endosperm hardness conditioned

Puffed maize using a cannon puffing machine has been scarcely studied. In this regard, Oscco-Quispe (2013) worked with hard yellow maize, while Rajha et al. (2021) evaluated different Peruvian maize samples (Morado, Chulpe, and Cancha). In both studies, the kernels were conditioned to 25–30 % moisture. However, maize exhibits considerable variability in shape, size, and endosperm hardness (López-Morales et al., 2023). Therefore, this stage aimed to evaluate the feasibility of obtaining puffed maize from kernels with different endosperm hardness.

The results showed that it is possible to pop dent maize classified as H, I, and S, with a flotation index between 28.5 and 75 % and varying 100-kernel weights (Table 2). In all cases, the proportion of semi-puffed kernels (PPK) was higher than that of unpuffed kernels (UPK) (Table 2). Additionally, high expansion volumes (VE) were obtained (19.4 to 21.89 cm³·g⁻¹), and no direct relationship was observed between endosperm hardness and VE. This contrasts with the hypothesis that harder maize produces higher VE, while softer maize generates lower

expansion volumes. No significant differences ($p > 0.05$) were found in UPK percentages or in kernel shape, with the butterfly form predominating. The moisture content of the puffed maize ranged from 2.57 to 5.28 %, with significant differences.

From this stage, it can be concluded that using a cannon puffing machine makes it possible to pop maize of different sizes and endosperm hardness, which would not pop with conventional methods (pan, microwave, and hot air). However, the mushroom shape, typical of puffed maize, did not predominate.

Native maize without conditioning

The results of this test demonstrated that it is possible to obtain puffed maize from kernels with varying endosperm hardness (Table 3), ranging from very hard (VH) to very soft (VS), with a FI of 5 to 95.5 %. However, in tests conducted with highly flourey maize (FI > 98 %), such as the Cacahuacintle and Conical landraces, it was observed that the kernels did not expand and were only toasted (data not shown).

The EV ranged from 11.07 to 25.72 cm³·g⁻¹, which is consistent with values reported for some popcorn maize hybrids (Zulkadir & Idikut, 2021). Similarly, low PPK and UPK values were obtained (Table 3), even lower than those reported using the pan-popping method, one of the most efficient for heat transfer to induce popping (Gökmen, 2004). No direct relationship was found between endosperm hardness and HWK with EV. However, the shape adopted by the kernel upon expansion (mushroom or butterfly) could influence EV. This is because butterfly-shaped puffed maize kernels have appendages that prevent compactness in the measuring cylinder, leaving empty spaces, whereas mushroom-shaped kernels are more compact (Figure 1) resulting in fewer empty spaces.

García-Pinilla et al. (2019) mention that in mushroom-shaped puffed maize kernels, the starch granule undergoes minimal expansion, maintains its structure, and retains the

Table 2. Comparison of grain characteristics and puffed quality variables in native maize with different endosperm hardness using a cannon puffing machine.

| Hardness | FI (%) | HKW (g) | EV (cm ³ ·g ⁻¹) | PPK (%) | UPK (%) | MS (%) | BS (%) | MPM (%) |
|----------|---------|----------|--|-------------------|---------|---------------------|---------|---------|
| H1 | 28.5 e | 33.85 ab | 20.81 ab | 0.24 b | 1.01 a | 34.56 a | 64.4 a | 3.18 cd |
| H2 | 33.5 de | 26.31 b | 19.88 ab | 1.79 ab | 0.45 a | 19.22 ab | 79.02 a | 2.57 d |
| I1 | 56.5 bc | 30.64 b | 17.42 c | 5.55 ^a | 1.32 a | 26.45 ab | 71.75 a | 3.5 c |
| I2 | 47.0 cd | 30.40 b | 20.08 ab | 3.26 ab | 0.0 a | 15.83 b | 81.75 a | 5.28 a |
| S1 | 75.0 a | 33.89 ab | 19.4 bc | 1.04 b | 0.69 a | 21.21 ab | 76.52 a | 4.98 ab |
| S2 | 67.0 ab | 45.22 a | 21.89 a | 0.66 b | 0.33 a | 19.09 ^{ab} | 77.67 a | 4.35 b |
| HSD | 15.54 | 11.52 | 2.36 | 4.46 | 3.09 | 15.78 | 27.26 | 0.72 |

H: hard; I: intermediate; S: soft; FI: flotation index; HKW: 100-kernel weight; EV: expansion volume; PPK: partially puffed kernels; UPK: unpuffed kernels; MS: mushroom shape; BS: butterfly shape; MPM: moisture content in puffed maize; 1 and 2: correspond to the analyzed population; HSD: honestly significant difference. Different letters within each column and each source of variation indicate significant differences (Tukey, $p < 0.05$).

Table 3. Comparison of mean values of kernel characteristics and popping quality variables in native maize with different endosperm hardness, without moisture conditioning, and processed in a cannon puffing machine.

| | FI (%) | HKW (g) | EV (cm ³ ·g ⁻¹) | PPK (%) | UPK (%) | MS (%) | BS (%) | MPM (%) | HPM (N) |
|-----|---------|---------|--|------------------|----------|-----------|-----------|----------|----------|
| VH1 | 5.0 g | 27.19 h | 22.93 ab | 0.31 a | 1.5 a | 66.12 cd | 33.88 ab | 4.23 a | 21.5 e |
| VH2 | 9.0 g | 29.43 g | 19.86 bc | 0.0 a | 0.0 c | 84.98 ab | 15.02 cd | 3.53 ab | 47.61 bc |
| H1 | 13.5 fg | 31.26 f | 25.72 a | 0.0 a | 0.0 c | 65.95 cd | 34.06 ab | 3.54 ab | 62.90 a |
| H2 | 29.0 ef | 21.45 i | 14.11 de | 1.3 a | 0.45 bc | 69.27 bcd | 30.73 abc | 2.55 cde | 65.61 a |
| I1 | 55.0 d | 38.95 e | 16.27 cd | 0.0 ^a | 0.96 abc | 77.74 abc | 22.27 bcd | 2.11 de | 33.52 d |
| I2 | 41.0 de | 56.74 c | 11.07 e | 0.84 a | 0.42 bc | 91.68 a | 8.32 d | 2.96bcd | 50.38 b |
| S1 | 73.5 c | 42.28 d | 25.0 a | 0.0 a | 0.0 c | 72.10 bc | 21.91 bc | 3.22 bc | 47.53 bc |
| S2 | 75.5 bc | 62.55 b | 21.72 ab | 0.93 a | 0.0 c | 64.41 cd | 35.60 ab | 3.38 abc | 43.87 c |
| VS1 | 95.5 a | 81.72 a | 18.42 bcd | 0.0 a | 0.12 c | 69.33 bcd | 30.67 abc | 3.38 abc | 43.67 c |
| VS2 | 91.5 ab | 42.45 d | 15.50 cde | 0.0 a | 1.41 ab | 54.60 d | 45.41 a | 1.82 e | 37.26 d |
| HSD | 17.98 | 0.53 | 4.58 | 2.31 | 1.0004 | 17.12 | 17.12 | 0.94 | 4.31 |

VH: very hard; H: hard; I: intermediate; S: soft; VS: very soft; FI: Flotation index; HKW: 100-kernel weight; EV: expansion volume; PPK: partially puffed kernels; UPK: unpuffed kernels; MS: mushroom shape; BS: butterfly shape; MPM: moisture content in puffed maize; HPM: hardness of puffed maize; 1 and 2: correspond to the population studied. HSD: honestly significant difference. Different letters within each column and each source of variation indicate significant differences (Tukey, $p < 0.05$).

hilum, which served as the pathway for water migration. In contrast, butterfly-shaped puffed maize kernels with more than one appendage likely form due to the presence of two main vapor release sites, which also generate larger cavities.

In the unconditioned kernels and at higher working pressure, the mushroom shape predominated (Table 3), which is typical of puffed products (Mariotti et al., 2006). The moisture content of the puffed maize (MPM) was slightly lower compared to that obtained from kernels conditioned to 14 % moisture (Tables 2 and 3), with a hardness ranging from 21.5 to 65.61 N, indicating a porous and crunchy texture.

Native maize processed in a semi-industrial cannon

Based on the previous results, which demonstrated the possibility of puffing kernels with different endosperm hardness (from very hard to very soft), maize with similar

hardness was selected for processing in a semi-industrial cannon (Table 4).

Under this condition, 100 % of the kernels expanded and maintained the mushroom shape (Table 4, Figure 3), with an average processing time of 11.36 min. The main difference between processing in the semi-industrial cannon and the laboratory cannon was the expanded volume, which was reduced by almost half (Tables 3 and 4). This can be attributed to the shape of the puffed kernel, as the absence of the typical appendages of the butterfly shape resulted in a smaller sample volume. The values of MPM and HPM ranged from 2.99-3.52 % and 35.86-54.21 N, respectively, similar to those obtained with the laboratory cannon (Table 3). It is important to mention that the puffed kernels were obtained from maize without moisture conditioning, which represents an advantage in processing. Several studies report the need to condition maize to high moisture levels for

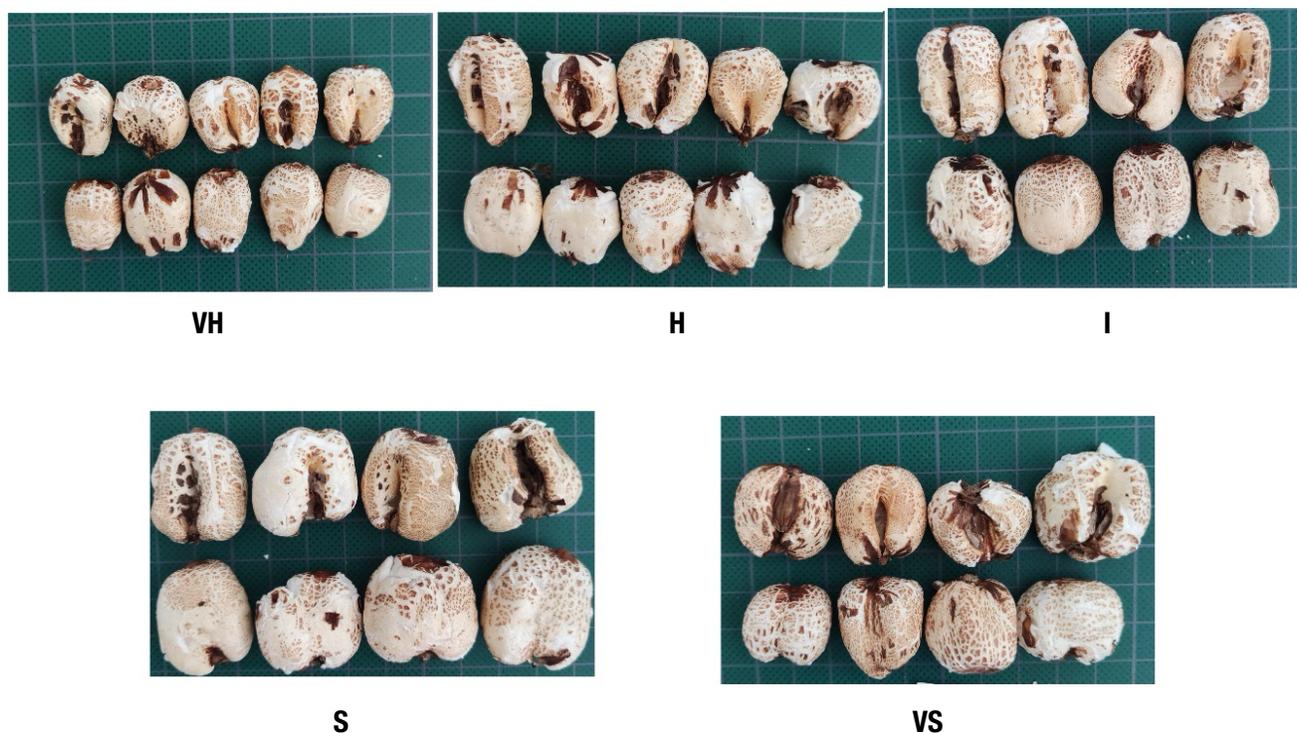


Figure 3. Native maize with different endosperm hardness processed in a semi-industrial cannon. The grid represents 1 cm². VH: very hard; H: hard; I: intermediate; S: soft; VS: very soft.

Table 4. Comparison of mean values of kernel characteristics and puffed quality variables in native maize with different endosperm hardness, without moisture conditioning, and processed in a semi-industrial cannon puffing machine.

| | FI (%) | HKW (g) | KM (%) | Processing time (min) | EV (cm ³ ·g ⁻¹) | MS (%) | MPM (%) | HPM (N) |
|-----|--------|---------|----------|-----------------------|--|--------|---------|----------|
| VH | 9.0 e | 26.13 e | 13.15 a | 11.19 a | 11.58 a | 100 | 3.08 b | 47.84 b |
| H | 36.0 d | 30.97 d | 12.15 bc | 11.28 a | 11.98 a | 100 | 3.52 a | 35.86 d |
| I | 63.0 c | 54.40 c | 11.75 c | 11.5 a | 11.93 a | 100 | 2.99 b | 54.21 a |
| S | 75.5 b | 62.56 a | 12.15 bc | 11.36 a | 12.0 a | 100 | 3.09 b | 41.49 c |
| VS | 93.5 a | 58.54 b | 12.4 b | 11.48 a | 11.8 a | 100 | 3.31 ab | 38.12 cd |
| HSD | 7.39 | 3.71 | 0.51 | 0.51 | 0.52 | | 0.39 | 3.41 |

VH: very hard; H: hard; I: intermediate; S: soft; VS: very soft; FI: Flotation index; HKW: 100-kernel weight; KM: kernel moisture; EV: expansion volume; MS: mushroom shape; MPM: moisture content in puffed maize; HPM: hardness of puffed maize. HSD: honestly significant difference. Different letters within each column and each source of variation indicate significant differences (Tukey, $p < 0.05$).

processing in expansion cannons (Mrad et al., 2014; Oscco-Quispe, 2013; Rajha et al., 2021). This requirement adds additional steps to the process and requires greater control, as increased moisture can raise the risk of fungal contamination.

Conclusions

Using the cannon puffing method, it is possible to obtain popcorn with low percentages of unpuffed kernels and a butterfly shape from ancient indigenous maize varieties that have lost their popping ability.

Conditioning the kernels to 14 % moisture allowed for high expansion volumes (19.4-21.9 cm³·g⁻¹) and butterfly-shaped puffed kernels. In contrast, higher operating pressure without moisture conditioning favored the formation of mushroom-shaped kernels, typical of puffed maize.

The expansion of native dent maize, with endosperm classified from very hard to very soft (floating indices from 9.0 to 93.5 %) and varying kernel sizes, is achievable using a semi-industrial cannon puffing machine operated at 1.03 MPa. The resulting product exhibits low moisture, along with desirable porosity and a crunchy texture.

In the context of new public policies promoting the reduction of junk food in schools, puffed maize represents a viable option as a healthy snack. Its production from native maize without a specific prior use allows for added value through a fast process that generates a ready-to-eat food product.

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