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Explosion Puffing of Native Mexican Maize: Physical Variables and Quality Assessment

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ABSTRACT

Snack consumption has become increasingly prevalent in modern dietary habits, largely driven by convenience. Puffed kernels represent a type of snack produced through the explosion puffing method, in which starch expansion is induced by pressure differentials. This study aimed to evaluate the puffing potential of different native maize populations by the explosion puffing method, identify variables associated with high-quality puffed kernels, and determine the proximate composition and total soluble phenol content of both raw and puffed kernels. The flotation index ranged from 5% to 98%, and maize samples was classified by endosperm hardness as very hard, hard, intermediate, soft, or very soft. Despite the wide variability in vitreous endosperm percentage, all hardness categories exhibited had a high proportion of puffed kernels (> 86.7%) and expansion volume between 10.1 and 26.6 cm^3 g^{-1}. Puffed kernels showed low moisture content (3.0%–3.6%), a porous and crunchy texture, high compressive force, and a preserved nutrient composition. Furthermore, the total soluble phenol content was higher in puffed kernels compared to their raw counterparts. This study provides an initial approach to utilizing dent maize for puffed kernel production, and demonstrates the effectiveness of explosion puffing in processing maize varieties with diverse physical characteristics.

Practical Applications

In Mexico, there is a wide diversity of maize that varies in size, color, shape, and hardness. Limited research has been conducted on the production of maize-based puffed products. In this study, we found that the explosion puffing method allows us to work with maize in a wide range of hardness, from very hard to very soft, but the highest puffing quality was achieved with hard and very hard maize. In the food industry, the use of this processing method can be promoted to process maize with varying hardness levels and to develop healthier snack alternatives, since the puffed kernels retain the nutritional properties of the raw kernel, including proteins and carbohydrates, while increasing their phenolic content.

1 | Introduction

The economic, social, and cultural changes of recent years driven a significant rise in the demand ready-to-eat foods (Ziena and Ziena 2022). In this context, consumer interest in snacks has grown due to appealing attributes, such as affordability, flavor, texture, and convenience, making them an important component of modern diets (Uliano et al. 2024).

The snack food market is dynamic and continually evolving, fueled by consumer demand for healthier options such as high-protein and high-fiber content products, low-fat alternatives, gluten-free items, and plant-based snacks. Its market value was projected to reach USD 747.65 billion by 2025, with savory snacks leading sales. Moreover, an annual growth rate of 4.3% has been forecast for the period between 2025 and 2030. (https://www.grandviewresearch.com/industry-analysis/snacks-market).

According to Serna-Saldivar (2022a), snacks are divided into three groups depending on the complexity of the elaboration process, first-generation snacks are those that have a minimal process, such as popcorn, nuts, fruits, and dehydrated vegetables. Second-generation snacks are obtained by grinding various types of grains, followed by kneading and finally extrusion (corn chips, tortilla chips, hard pretzels, etc.) and finally third-generation snacks refer to more elaborate products where many ingredients are used in their formulation and which require additional processes to reach the consumer.

Maize is the most widely produced cereal in the world; currently, 1,241,801,714 tons are produced (FAOSTAT 2024). It is also one of the cereals most extensively used in snack manufacturing, either as alkaline-cooked maize products (such as corn chips and tortilla chips) or as popcorn (Serna-Saldívar 2022b).

At the industrial level, the production of alkaline-cooked maize-based snacks relies on hard-endosperm (flotation index (FI) > 12%) and small-grain maize (Gaytán-Martínez et al. 2013). In contrast, popcorn is produced exclusively from the specialty maize variety known as popcorn (Serna-Saldívar 2022b), thereby excluding maize with other hardness levels from industrial applications.

Mexico harbors the greatest diversity of maize, with 59 registered native varieties encompassing a wide range of grain shapes, sizes, and hardness levels (CONABIO 2020). This diversity includes ancient indigenous races such as Palomero Toluqueño, Arrocillo, Chapalote, and Nal-Tel, all originally classified as popping maize (Wellhausen et al. 1951). Over time, however, the interbreeding of their germplasm with other maize types has resulted in the gradual loss of their popping trait (Bautista-Ramírez et al. 2020).

The popping of popcorn kernels is influenced by several intrinsic factors, including pericarp thickness, internal moisture, kernel shape (pearl or rice), size, a high proportion of vitreous endosperm, and lipid and protein content (Sweley et al. 2013), characteristics absent in dent maize. In addition, popping performance depends on interactions with the production environment (Gopinath et al. 2024), storage time and temperature (Allred-Coyle et al. 2000), and the popping method employed (hot air, microwave, or pan; Luzardo-Ocampo et al. 2025), among other factors. Dent maize, due to its kernel shape and hardness, is unsuitable for popping with conventional methods such as hot air, microwave, or pan. In this context, the use of an expansion barrel could enable the production of puffed maize, providing a valuable alternative for native maize landraces that lack the inherent popping capacity characteristic of popcorn.

Puffed grains (PGs) are traditional snacks produced from various cereals such as rice, wheat, oats, sorghum, and, more recently, maize. They are characterized by a crunchy, porous texture (Huang et al. 2018; Lee et al. 2019; Rajha et al. 2021). Unlike extrusion puffing, which employs semolina or flour and requires preliminary unit operations such as homogenization, conditioning, and kneading, explosion puffing uses whole grains, resulting in a superior nutritional profile in the final product (Mounir et al. 2023). In explosion puffing, kernels are placed in a hermetically sealed expansion chamber that is heated to increase internal pressure (Lee et al. 2019; Rajha et al. 2021). When the chamber is suddenly opened, the grains expand due to the pressure differential, and the PGs obtained through this method retain their shape (Mariotti et al. 2006).

In popcorn, small kernels with a low proportion of floury endosperm have been shown to achieve the highest popping volumes. This is primarily because the vitreous endosperm plays a dominant role in kernel expansion during popping, through starch gelatinization and the formation of a three-dimensional foamy structure (Sweley et al. 2013; Vázquez-Carrillo et al. 2019). Nevertheless, the presence of a small central region of floury endosperm is also relevant, as it can accumulate greater pressure prior to popping, thereby resulting in larger popping volumes (Sweley et al. 2013). In this regard, Nguyen et al. (2024) reported that popcorn genotypes containing 21%–22.5% floury endosperm exhibit higher popping yields compared to those with lower proportions (12%–20%). Therefore, this study evaluated the physical characteristics of 39 native maize populations with varying endosperm hardness, collected from the states of Puebla, Guerrero, and Veracruz. The quality of the puffed kernels was determined, its correlation with the physical attributes of the kernels was analyzed, and the proximate composition as well as the phenolic content of both raw and puffed kernels were assessed.

2 | Materials and Methods

2.1 | Genetic Material

Thirty-nine populations of native maize from the states of Puebla, Guerrero, and Veracruz were studied, which presented kernels of contrasting hardness, ranging from very hard to very soft. In the present study, 14 populations of Pepitilla landrace, six populations of Ancho landrace, two populations of Arrocillo landrace, two populations of Tuxpeño landrace, one population of Cónico landrace, one population of Bolita landrace, one population of Elotero de Sinaloa landrace, and one more of Zapalote Chico landrace were represented, and the rest were introgressions: Tablilla de Ocho × Pepitilla, Bolita × Pepitilla, Arrocill6o × Bolita, Chalqueño × Pepitilla (2), Arrocillo × Cónico, Pepitilla × Chalqueño, Vandeño × Pepitilla, Vendeño × Celaya, Elotero de Sinaloa × Ancho, and Elotes Occidentales × Pepitilla.

2.2 | Grain Physical Characterization

The test weight (TW), FI, hundred grain weight (HGW), and percentage of kernel structures (pedicel [PD], pericarp [PR], germ [G], floury endosperm [Floury E], and vitreous endosperm [Vitreous E]) were evaluated according to Vázquez-Carrillo et al. (2023). The FI was determined using a $NaNO_3$ solution with a density of 1.25 g·mL^{-1}. A total of 100 clean kernels were deposited in the solution, subsequently counted and the endosperm hardness was classified according to the percentage of floating kernels as follows: very hard (0%–12%), hard (13%–37%), intermediate (38%–62%), soft (63%–87%), and very soft (> 88%; Secretaría de Economía 2022).

2.3 | Puffed Quality

From each maize landrace, 70 g of clean, mechanically undamaged grains were taken, and three replicates were made to evaluate PG quality. The sample was placed in an expansion barrel and heated for 4–5 min until the working pressure (1.18 MPa) was reached. The barrel was then suddenly opened to allow the pressure difference to cause the grains to expand. The variables measured were of percentage PGs, puffed size (PS [cm^3 grain^{-1}]), expansion volume (Exp. Vol. [cm^3 g^{-1}]), moisture (%), and compression force (N).

Grains were counted before and after puffing. The percentage of PGs was determined using Equation (1). The volume of PGs was measured in a 2000 mL graduated cylinder with an internal diameter of 8.5 cm. The expansion volume and PS were calculated using Equations (2) and (3), respectively (Ceylan and Karababa 2001).

$$PG = [(\text{Number of puffed kernels}) / (\text{Original numer of kernels})] \times 100 \tag{1}$$

$$\text{Exp.Vol.} = \text{Puffed kernels volume}\left(cm^3\right)/\text{Original sample weight}\,(\text{g}) \tag{2}$$

$$PS = \text{Puffed kernels volume}\left(cm^3\right)/\text{Numberofpuffed kernels} \tag{3}$$

The percentage of moisture was determined by the gravimetric method 44-15.02 of the American Association of Cereal Chemists (AACC 2020). The compression force was evaluated on 10 PGs per replicate puffing, which were randomly selected. A texturometer (Brookfield CT3 model, Middleboro, MA, USA) with a 25 kg load cell and spherical probe of 25.4 mm diameter was used, the test parameters were 1 mm s^{-1} test speed and a target value of 20 mm, and the results were expressed in Newtons. Each grain was evaluated individually.

2.4 | Proximate Analysis

Moisture content, crude fat, protein, crude fiber, and ash were determined in both grain and puffed gran by methods 44-15.02, 30-10.01, 46-10.01, 32-10.01, and 08-02.01 of the American Association of Cereal Chemists (AACC 2020), while carbohydrates were calculated by difference.

2.5 | Total Soluble Phenols Content (TSP)

One hundred mg of flour were weighed and placed in 2 mL Eppendorf tubes, to which 1.8 mL of 80% methanol acidified with 1% trifluoroacetic acid (TFA) was added. The samples were sonicated for 15 min in a Branson ultrasonic bath (model 2510-MTH, Branson Sonic Corporation, Danbury, CT, USA) and then placed under refrigeration for 105 min. Subsequently, the samples were centrifuged at 6720 × g for 10 min in a microcentrifuge (model Z 200M/H, Hermle-Labortechnik, Wehingen, Germany), the supernatant was decanted, and the volume was adjusted to 2 mL using the extraction solvent.

TSP quantification was performed using the Folin–Ciocalteu method adapted for microplates (Hernández-Rodríguez et al. 2016). To each well 20 µL of extract was added, followed by 125 µL of distilled water, then 20 µL of 0.2 N Folin solution and finally 30 µL of 20% Na_2CaO_3. The reaction was allowed to stand in the dark for 30 min, and the absorbance was read at 760 nm using an Epoch plate reader (Epoch, Biotek Instrument, Winooski, VT, USA). A ferulic acid standard curve was generated, and the content was expressed as mg of ferulic acid equivalents (FAEs) per 100 g of dry sample.

2.6 | Data Analysis

All variables were measured in triplicate. The grain structure and proximate composition variables in raw and PGs were analyzed using descriptive statistics (indicators of central tendency, dispersion, and asymmetry). The 39 maize populations were classified according to kernel hardness; for FI, hundred-grain weight, TW, puffed quality, and phenolic content, box-and-whisker plots were used to identify trends or behaviors in the groups. The data were analyzed with a Kruskal–Wallis test, followed by comparison of mean ranks using the Dunn's post hoc test with Bonferroni adjustment to control for type 1 error. A significance level of 0.1 was used. A Pearson correlation analysis was performed with the grain and puffed quality variables, from which the least correlated variables were discarded, and a principal component analysis was performed with the rest to obtain greater variance explained in the first two components. Indicators of central tendency, dispersion, and asymmetry were calculated using Excel software and graphs were generated using RStudio software version R-4.4.2 with the Factoextra, FactoMineR, and ggplot2 libraries. The Kruskal–Wallis test was performed using the IBM SPSS Statistics 22 software.

3 | Results and Discussion

3.1 | Grain Physical Characterization

Statistical analysis showed that there were significant differences between the variables IF, HGW, and TW according to the type of endosperm hardness (Figure 1).

According to the FI, five populations were classified as very hard endosperm (5%–10%), eight populations as hard endosperm (13.5%–33.5%), six populations as intermediate hardness (41%–61.5%), eleven populations as soft endosperm (65.5%–82.5%), and nine populations as very soft (88%–98%; Figure 1A). The greatest dispersion was found in the hard, intermediate, and soft maize groups.

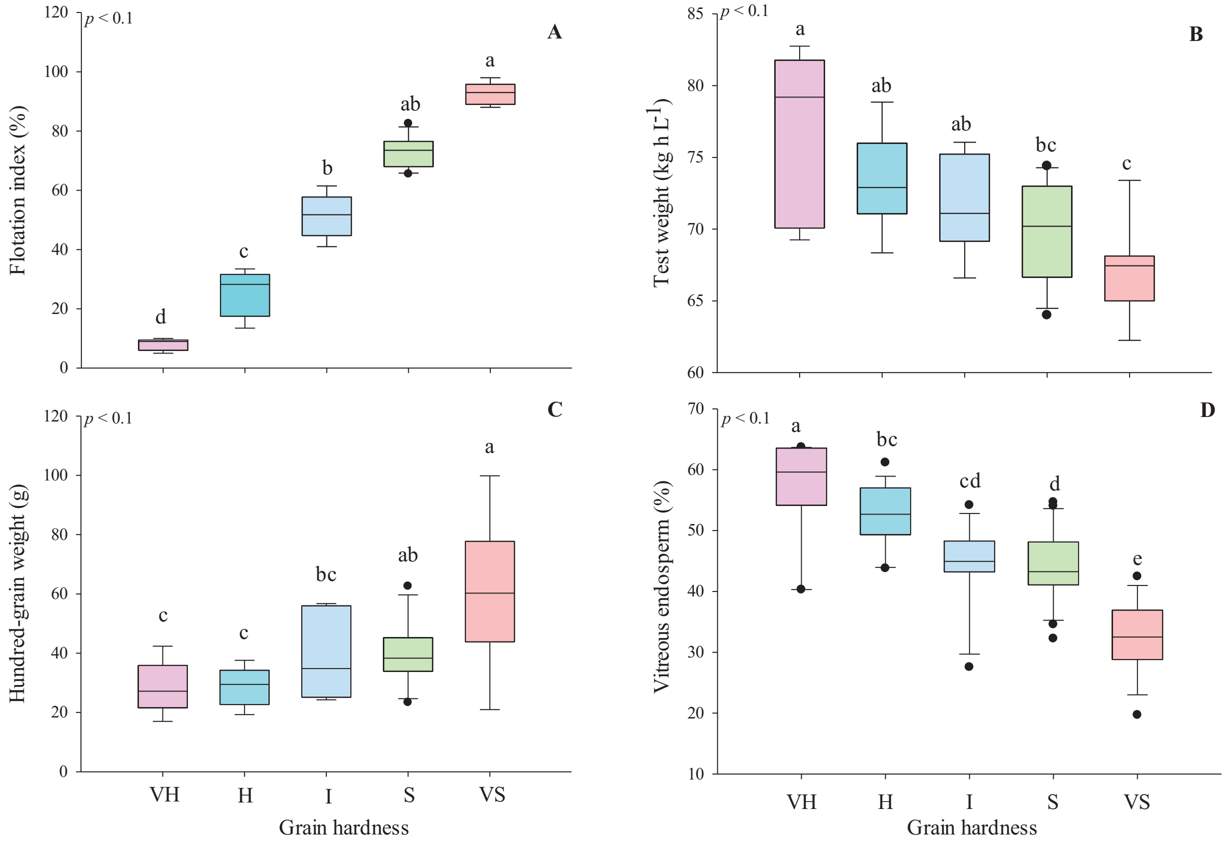

FIGURE 1 | Flotation index (A), test weight (B), hundred grain weight (C), and percentage of vitreous endosperm (D) of 39 native maize from the states of Puebla, Guerrero, and Veracruz, collected during the spring–summer cycle of 2023. H, hard; I, intermediate; S, soft; VH, very hard; VS, very soft. Different lowercase letters indicate a significant statistical difference.

Grain size was different for each group of maize classified by hardness. The smallest grains were found in maize classified as VH and H with HGW between 17–42 g (Figure 1C), in the rest of the groups, there was greater variation, mainly in VS, with HGW from 20.9 to 99.9 g (Figure 1C). This is explained by the fact that in this category most populations of the Ancho landrace were represented, which stands out for its large kernel size (Hernández-Galeno et al. 2014), whereas the lowest value in this category corresponded to the Zapalote Chico landrace.

The TW is a method of measuring kernel density, and like the FI, it is closely related to kernel hardness, so that the maize classified as VH and H had the highest TW (70–82 kg hL^{-1}, Figure 1B). In these classifications were represented the landraces Pepitilla, Arrocillo, and Tuxpeño, and the introgressions Tablilla de Ocho × Pepitilla, Bolita × Pepitilla, and Arrocillo × Bolita. Maize classified as VH had the widest range (13.5), and it was in this classification where the highest TH was found (82.8 kg hL^{-1}), corresponding to the Tuxpeño landrace. On average, the maize classified as VS had a lower TW (67.1 kg hL^{-1}), which is also due to the larger grain size (Salinas-Moreno et al. 2013). The landraces represented in this group were Ancho, Zapalote Chico, Elotero de Sinaloa, and Pepitilla, and the introgressions were Elotero de Sinaloa × Ancho, and Elotes Occidentales × Pepitilla. In processes such as nixtamalization, the physical characteristics of the grain are very important because they determine the conditions of the process, for example, the nixtamalization time. In addition, grain size influences water absorption (Salinas-Moreno et al. 2013), and lower fuel consumption during nixtamalization is associated with rapid water absorption and lower grain hardness (Roque-Maciel et al. 2016). In the production of puffed maize, the physical characteristics that the grains must have to obtain the highest quality have not yet been established; in this regard, García-Cruz et al. (2023) found that it is possible to obtain puffed maize using hard, intermediate, and soft grains.

The structural composition of the 39 populations was similar in terms of pedicel, pericarp, and germ structures because the dispersion variables are low, in addition to the fact that their distribution is similar to the standard distribution (Table 1), although according to the symmetry coefficient slightly skewed to the right (pedicel and germ). The greatest variation was observed for endosperm types, as indicated by central tendency and dispersion variables (Table 1). This is because, as mentioned above, the populations were classified into five types according to kernel hardness (very hard, hard, intermediate, soft, and very soft), where the populations with the highest FI had the highest proportion of floury endosperm, while those corresponding to the classification of VH, H, and I had the highest proportion of vitreous endosperm (Figure 1D). The vitreous endosperm, due to the arrangement of starches, causes greater weight and density, whereas the floury endosperm is arranged in spherical granules that leave more empty spaces, resulting in less weight and density in the grain. Similar results in kernel structure were reported by López-Morales et al. (2023), who analyzed 15 maize populations ranging from very hard to very soft.

TABLE 1 | Indicators of central tendency, dispersion, and symmetry of the structural composition of kernels of 39 populations of native maize from the states of Puebla, Guerrero, and Veracruz, collected during the spring–summer cycle of 2023.

		Pedicel	Pericarp	Germ	Floury E
Central tendency	Mean	1.6	5.4	11.7	36.6
	Median	1.6	5.3	11.7	36.4
	Mode	—	—	—	—
Dispersion	Standard deviation	0.3	0.8	1.0	10.5
	Variance	0.1	0.6	1.1	107.7
	Coefficient of variation	22.2	14.1	8.9	28.7
	Range	2.0	3.3	4.5	40.5
	Minimum	0.9	3.9	9.4	17.3
	Maximum	2.9	7.2	13.9	57.9
Symmetric	Kurtosis	4.9	0.0	0.0	−0.6
	Asymmetric coefficient	0.9	0.3	−0.4	0.1

In the case of popcorn, the thickness of the pericarp and the proportion of vitreous endosperm are very important variables because they are closely related to the volume of expansion. Thus, the greater the thickness of the pericarp and the percentage of vitreous endosperm, the greater the expansion of the kernels (Freire et al. 2020). When evaluating maize from the whole spectrum of hardness classification, it is important to characterize its structural composition of its kernels (Table 1 and Figure 1D) to identify correlations with puffed quality variables. However, more studies on amylose content and starch granule size are needed to achieve a better characterization.

3.2 | Puffed Maize Quality

Using the expansion barrel, PG percentages ranged from 86% to 100%, with no statistical differences between the hardness groups analyzed (Figure 2A), where the populations classified as VH, H, and I had the least variation because the box and whisker plots corresponding to these classifications were more compact. This behavior could be due to the higher vitreous endosperm content in grains classified as VH, H, and I (Figure 2D), as it has been reported that highly compacted vitreous starch expands more compared to floury starch (Vázquez-Carrillo et al. 2019). Nevertheless, 75% of the populations classified as S and VS, grains had PG percentages close to 100%. In popcorn landraces, such as Palomero Toluqueño (Bautista-Ramírez et al. 2020) and Chapalote (Vázquez-Carrillo et al. 2019), lower percentages were obtained than those obtained in the present work, where most of the maize landraces used were not poppers. This highlights the capacity of the method used to expand the grains, since the percentage of PG was high. In the studies mentioned above, they used the microwave, forced hot air, and frying pan with oil methods.

The expansion volume ranged from 10.1 to 26.6 cm^3 g^{-1} (Figure 2B). The highest values were found in kernels classified as VH, followed by H (integrated by Tuxpeño, Pepitilla, and Arrocillo landraces), which could be influenced by kernel size, since in these classifications the smallest grains were found (Figure 1B), and Vázquez-Carrillo et al. (2019) mentioned that small kernels with higher vitreous endosperm content produce higher expansion volumes. However, the correlation analysis did not reveal significance between the variables mentioned above (Figure 3A). The expansion volumes were high, compared to what was reported for the Palomero Toluqueño landrace kernels popped in microwaves (1.0–7.25 cm^3 g^{-1}; Bautista-Ramírez et al. 2020). One of the main quality parameters in popcorn is the expansion volume, where the minimum required value is 35 cm^3 g^{-1} (Sweley et al. 2013). In the present work, 51% of the analyzed populations had a Exp. Vol. $\geq$ 20 cm^3 g^{-1}, which is comparable to that obtained in popcorn developed by genetic improvement programs (6.2–20.6 cm^3 g^{-1}; Zulkadir and İdikut 2021).

PS ranged widely from 3.6 to 21.4 cm^3 grain^{-1} (Figure 2C), and was highly correlated with grain size (Figure 3A), because populations classified as VH and H grains presented the lowest PS and HGW values. On the other hand, in the populations classified as very soft, the highest PS (21.4 cm^3 grain^{-1}) corresponded to a population of the Ancho landraces with a HGW of 99.9 g.

It should be noted that, unlike popcorn, which must be conditioned at 11.4% moisture to obtain the highest popping quality (Corrêa Cañizares et al. 2020), or 13.5%–14.5% (Serna-Saldivar 2022b), the maize used in the present work was not conditioned, and kernel moisture ranged from 9.3% to 13.6% (data not shown); however, moisture did not affect the puffed quality variables. In this regard, Mrad et al. (2014) conditioned the grain of two maize varieties with humidity between 20% and 30% and used intensification of vaporization by decompression to the vacuum as the expansion method. They found that the initial humidity had no significant effect on the rate of grain expansion.

The average moisture and standard deviation (bars) of the PGs of each evaluated group are shown in Figure 2D, ranging from 3.0% to 3.6%. No trends between groups are visualized, so it can be said that the hardness of the kernel does not influence the final moisture of the PGs. In popcorn obtained by the microwave method, moisture values (4.8%; Ranathunga et al. 2016) similar to those obtained in the present work have been reported.

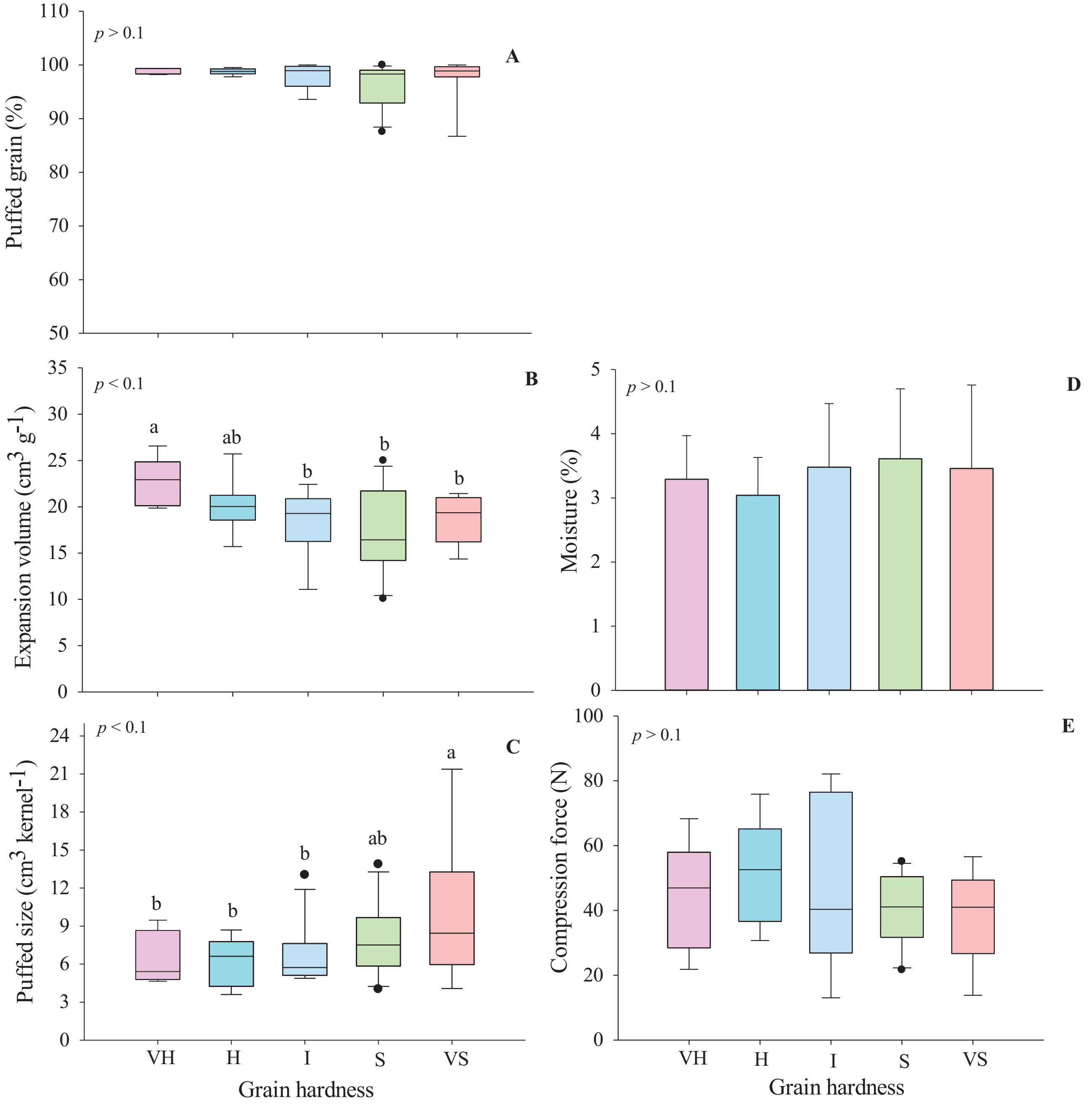

FIGURE 2 | Puffing quality variables for 39 native maize from the states of Puebla, Guerrero, and Veracruz, collected during the spring–summer cycle of 2023. Puffed grain percentage (A), expansion volume (B), puffed size (C), moisture (D), and compression force (E). H, hard; I, intermediate; S, soft; VH, very hard; VS, very soft. Different lowercase letters indicate a significant statistical difference.

On the other hand, the texture of the PGs varied widely depending on kernel hardness (Figure 2E); the kernels classified as S and VS had lower values (13.8–55.1 N) and shorter ranges (box-and-whisker plot width) than the VH, H, and I kernels. In popcorn, hardness values between 17 and 21 N have been reported (Park and Maga 2001). Only 12.8% of the studied populations fall below or between these values. However, the shape of the PG must be considered. The PGs shape is compact (Figure 3C), without appendages as in the case of butterfly-shape popcorn, and therefore, a greater force is required to fracture the PG. Medellín-Cruz et al. (2025), in contrast, reported higher hardness values (62.1–284.1 N) in popcorn made by three methods (oil, air, and microwave). This evidences that the method used to measure hardness influences the results. In this respect, Gopinath et al. (2024) mention that popcorn made from rice-type kernels has better popping quality than that made from pearl-type kernels. Additionally, Mariotti et al. (2006) found that the size of the internal cavities of puffed kernels varies according to the species used. Puffed rice forms a porous matrix composed of cavities of different sizes. In contrast, emmer wheat and barley produce a more compact, homogeneous and less porous structure, and puffed buckwheat generates small, irregular cavities.

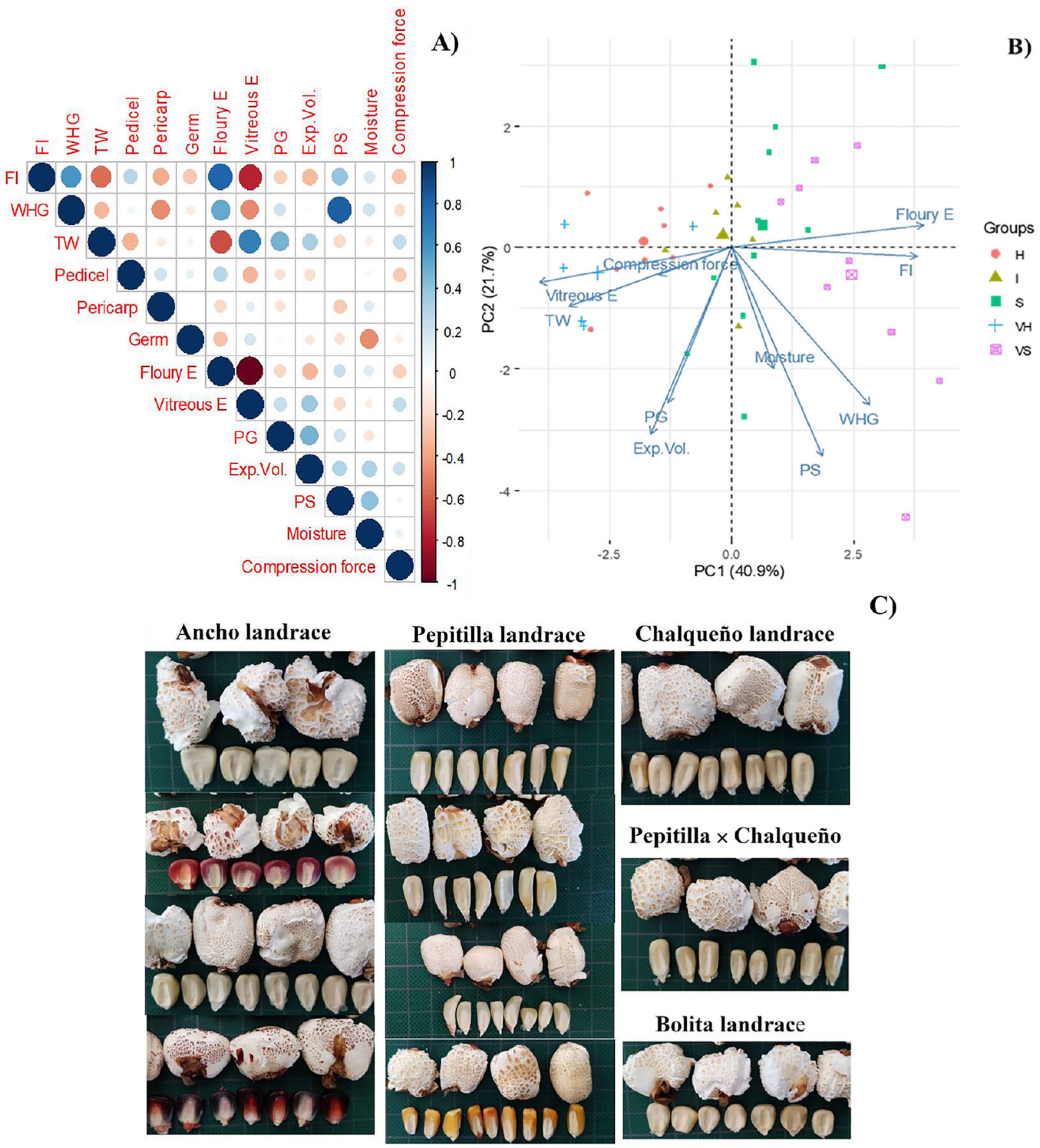

FIGURE 3 | Pearson's correlation of the physical variables of the grain with the puffing quality variables (A), analysis of the two principal components, and distribution of the landraces analyzed classified by the hardness of their grains, H, hard; I, intermediate; S, soft; VH, very hard, VS, very soft (B), appearance of the raw grain, and puffed grain of some of the landraces represented in the present study (C). Each square in the grid in Figure 4C represents 1 cm.

The physical variables that correlated positively with the puffing quality variables were HGW, TW, FI, and vitreous endosperm, whereas the variables that correlated negatively were floury endosperm and germ, the former affecting the expansion volume and the latter affecting the moisture content in the puffed maize (Figure 3A). However, the only significant correlation was between HGW and PS. Principal component analysis (Figure 3B) shows the distribution of the first two components of the 39 populations classified according to kernel hardness, which explained 62.6% of the variability of the data. The larger symbols in each group indicate the mean position. Populations classified as VH and H were located in the second and third quadrants and were characterized by the highest values of vitreous endosperm, compression force, and TW. Populations classified as VS were located in the first and fourth quadrants and were characterized by the highest values of floury endosperm, FI, and HGW. Populations classified as I and S were distributed toward the center. Most of the populations studied were located in opposite positions to the vectors of the puffing quality variables (PG, Exp. Vol., PS, Moisture and Compression force), and only three populations classified as S and one I were oriented toward these vectors; therefore, the study cannot be conclusive as to whether certain types of hardness originate the highest puffing quality; however, information was generated that can be the basis for future experiments. One of the main characteristics of puffed cereals is that, by using the whole grain, it expands and assumes a shape closely resembling that of its original form. In this work, we had maize with a great diversity of sizes (Figure 1B) and shapes (Figure 3C), such that the grains with a flat shape gave rise to rounded and globular puffed, such as those of the Ancho and Bolita landraces; while the elongated grains, such as those of the Pepitilla and Chalqueño landraces, gave rise to globular and elongated puffed (Figure 3C). This is a challenge to overcome, because although each maize landraces is characterized by a particular shape of its kernels, this shape depends on the position in which they are located on the cob, since the kernels at the base are usually larger than those at the center, and the kernels located at the top of the cob are the smallest, so to achieve uniformity in the puffed, the kernels must be sieved to homogenize the kernel size.

3.3 | Chemical Composition of the Grains and Puffings

According to the mode, the proximate compositions of most of the evaluated populations were 1.3% ash, 1.9% crude fiber, 5.6% crude fat, 10.3% protein, and 81.6% carbohydrates (Table 2). The variables with the greatest variation, and therefore the greatest range, were crude fat, protein, and carbohydrates (Table 2). The populations with the highest content had 3.3%, 8.0%, and 12.5% for these variables, respectively. Ash and fiber contents were similar to those reported by Rodríguez-Salinas et al. (2020) in native maize from Northeastern Mexico. In terms of crude fat content, the results obtained are higher than those reported in different native maize collections, where values range from 4.2% to 5.3 % (Broa Rojas et al. 2019; Salinas-Moreno et al. 2013). Protein contents were higher than those reported by Broa Rojas et al. (2019) for native maize from the state of Morelos, with values of 8.3%–8.9%, but were similar to those reported by (Vázquez-Carrillo et al. 2010) for native maize from the state of Hidalgo, México (8.2%–12.4%).

The average compositions of the PGs were 1.3%, 1.5%, 5.1%, 9.8%, and 82.1% for ash, crude fiber, crude fat, protein, and carbohydrates, respectively (Table 2). The components where there was a slight reduction from raw to puffed were crude fiber, crude fat, and protein contents; as these components decreased, the carbohydrate content increased because they were calculated by difference. The reduction in crude fiber content is explained by the fact that during the expansion of the grain, the pericarp fractures and pulverizes, leaving only a part of it adhered to the grain. The decrease in protein content was due to the loss of part of the aleurone layer during the expansion process (Mariotti et al. 2006), so the decrease in total protein content could be related to the loss of this structure, since although the highest protein content is found in the endosperm, proteins are also found in the aleurone layer (Zheng and Wang 2014). It has been reported that in PGs, proteins are denatured by pressure and elevated temperature, resulting in smaller molecules (peptides) and amino acids (Jia et al. 2021), which improves their digestibility (Huang et al. 2018). Regarding crude fat reduction, the high pressure could have expelled some of the oil out from the germ, similar to when oil extraction by pressing (Barrera-Arellano et al. 2018), however, reduction in crude fat content due to the formation of amylose–fat complexes (Huang et al. 2018) has also been observed. The method used to obtain PGs does not add any extra ingredients to the process, unlike the frying pan method with oil, which is one of the most commonly used to obtain popcorn, and causes an increase in the crude fat content in the final product (Paraginski et al. 2016).

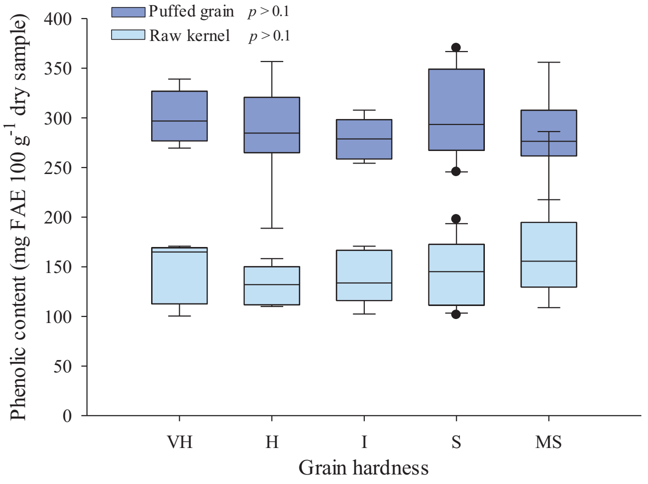

FIGURE 4 | Phenolic content in raw kernels and puffed grains of 39 native maize from the states of Puebla, Guerrero, and Veracruz, collected during the spring–summer cycle of 2023. H, hard; I, intermediate; S, soft; VH, very hard; VS, very soft.

3.4 | Phenolic Content in Raw and Puffed Grains

The content of soluble phenols in the raw grain showed a wide variation that ranged from 100.4 to 286.2 mg FAE/100 g^{-1} of dry sample (Figure 4); the highest values were presented in the populations classified as VS because in this classification there were three pigmented populations, corresponding to the Elotero de Sinaloa, Elotero de Sinaloa × Ancho, and Elotes Occidentales × Pepitilla landraces, and it has been reported that pigmented maize has higher phenolic content with respect to white maize (Rodríguez-Salinas et al. 2020). In 61.5% of the evaluated populations, soluble phenol contents ≥ 130 mg FAE/100 g^{-1} dry sample were higher than those reported by Guzmán-Maldonado et al. (2015) for white native maize (82.2–120 mg gallic acid equivalents per 100 g sample). However, the differences could have been influenced by the standard used in the quantification. Nevertheless, the results were similar to those found by Vukadinović et al. (2024) for yellow popcorn (149–256 mg FAE/100 g^{-1}).

The content of soluble phenols in the PGs increased in a similar rate for all the hardness levels analyzed, ranging from 188.8 to 370.4 mg FAE/100 g^{-1} dry sample (Figure 4). It has been reported that the concentrations of bound phenols are higher than those of free phenols (Das and Singh 2015), so the increase in phenolic content in the PGs could be due to the fact that the bound phenols were released by the action of elevated temperature and pressure and trapped in the expanded starch. Similar behaviors have been observed in popcorn of different colors, where the phenolic content increased in the popping grain (Kayişoğ and Anil 2023; Paraginski et al. 2016).

In the PGs from the VS group, the phenolic content decreased with respect to the other classifications (VH, H, I, and S). This behavior was due to the fact that, in the pigmented maize populations the anthocyanins (responsible for the color) were completely degraded (Figure 3C) due to the high temperature and pressure of the process. Anthocyanins are highly sensitive

TABLE 2 | Indicators of central tendency, dispersion, and symmetry of the proximate composition of the raw and puffed grains of 39 populations of native maize from the states of Puebla, Guerrero, and Veracruz, collected during the spring–summer cycle of 2023. The contents are expressed as percentages.

		Raw kernel				
		Ash	**Crude fiber**	**Crude fat**	**Protein**	**Carbohydrate**
Central tendency	Mean	1.3	2.0	5.7	10.2	80.2
	Median	1.3	2.0	5.6	10.1	80.4
	Mode	1.3	1.9	5.6	10.3	81.6
Dispersion	Standard deviation	0.2	0.5	0.7	0.9	1.6
	Variance	0.0	0.3	0.5	0.8	2.3
	Coefficient of variation	11.7	26.3	12.0	8.8	2.0
	Range	0.6	2.1	3.6	5.2	6.2
	Minimum	1.0	1.2	4.4	7.3	76.4
	Maximum	1.5	3.3	8.0	12.5	82.6
Symmetric	Kurtosis	0.4	0.4	2.6	2.4	1.4
	Asymmetric coefficient	−0.6	0.7	0.9	−0.3	−1.0

		Puffed grain				
		Ash	**Crude fiber**	**Crude fat**	**Protein**	**Carbohydrate**
Central tendency	Mean	1.3	1.5	5.1	9.8	82.1
	Median	1.3	1.5	5.1	9.8	82.1
	Mode	1.1	1.5	—	9.9	—-
Dispersion	Standard deviation	0.18	0.37	0.50	0.92	1.1
	Variance	0.03	0.13	0.24	0.79	1.2
	Coefficient of variation	14.0	24.6	9.8	9.4	1.4
	Range	0.6	1.4	2.4	4.1	4.1
	Minimum	1.0	1.1	4.1	7.6	80.4
	Maximum	1.6	2.5	6.5	11.7	84.4
Symmetric	Kurtosis	−0.7	1.7	2.4	2.3	−0.4
	Asymmetric coefficient	0.5	1.1	0.5	−0.1	0.3

to thermal degradation; the degradation mechanism involves deglycosylation of the anthocyanin, opening of the pyrylium ring and the formation of the chalcone, which due to its thermolability is immediately degraded to a phenolic acid and an aldehyde (Sadilova et al. 2007), compounds that lack color. In blue popcorn, a 46% reduction in anthocyanins has been reported using the microwave method (Lago et al. 2013), however, high processing temperature combined with high pressure increases anthocyanin degradation (Buckow et al. 2010), such that in puffed black soybeans, a 93% loss of anthocyanins has been reported using 784 kPa pressure during expansion gun processing (Kim et al. 2020).

4 | Conclusions

Although none of the evaluated physical characteristics showed a significant correlation with puffing quality, the highest quality was observed in maize classified as very hard and hard. This was evidenced by the highest percentage of puffed kernels, greater expansion volume, and optimal puffing moisture. Nonetheless, puffed kernels were also obtained from maize populations with intermediate, soft, and very soft hardness. Puffed maize can be an alternative for healthy snacks since the nutritional composition of the grain is maintained and its phenolic content is improved compared to raw kernels. The use of the expansion barrel makes it possible to work with dent grains that do not have the characteristic of specialty maize such as popcorn; thus, this technique could provide greater added value. The production of puffed maize by the expansion barrel method yields ready-to-eat food in a short time. This versatile food can be consumed either as a sweet or salty snack; however, additional research is required to determine the level of sensory acceptance among consumers.

Author Contributions

Leticia García-Cruz: methodology, validation, formal analysis, investigation, writing – original draft, writing – review and editing, supervision, visualization, conceptualization. **María Gricelda Vázquez-Carrillo**: validation, formal analysis, resources, writing – original draft, supervision, project administration, funding acquisition, investigation, conceptualization. **César del Ángel Hernández-Galeno**: methodology, project administration, funding acquisition, investigation. **Pedro Antonio-López**: methodology, investigation. **Fernando López-Morales**: investigation, methodology.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data will be made available upon request.

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