Article

# Expansion volume of amaranth grain in local populations and improved varieties

Ana Rosa Ramírez-Pérez[1]
Enrique Ortiz-Torres[1§]
Adrián Argumedo-Macías[1]
Micaela De la O-Olán[2]
Carmen Jacinto-Hernández[2]
Ignacio Ocampo-Fletes[1]

[1]Postgraduate College-Puebla Campus. Boulevard Forjadores the Puebla num. 205. Santiago Momoxpan, San Pedro Cholula, Puebla, Mexico. ZC. 72760. (anarosa-rmz@yahoo.com.mx; aadrian@colpos.mx; agroecologia-iof@yahoo.com). [2]Mexico Valley Experimental Field-INIFAP. The Reyes-Texcoco Highway km 13.5, Chapingo, Texcoco, State of Mexico, Mexico. AP. 10. ZC. 56230. (micaelaolan@yahoo.com.mx).

[§]Corresponding author: enriqueortiz@colpos.mx.

## Abstract

In Mexico, the common form of commercialization and consumption of amaranth is as popped grain. However, there are few studies on the diversity in the expansion volume of grain in amaranth species and populations. The objective was to assess the diversity in expansion volume of grain in 36 local populations and improved varieties of amaranth. Grains from a field evaluation in four locations carried out in 2015 and 2016 were used. A 6 x 6 lattice experimental design with two repetitions was used. In 2018, the expansion volume of popped grain was evaluated. Thirty-six varieties of amaranth were used, of which 30 were populations of the municipality of Tochimilco, Cohuecan and Huaquechula, Puebla, Mexico and the Amaranteca, Benito, Nutrisol, Revancha, Laura and Gabriela varieties. The samples were conditioned to 12% moisture and popped in fluidized bed machine by hot air at a temperature of 230-235 °C. After the popping, the weight and volume of the grain popped and not popped were recorded. An analysis of variance and mean test were performed. The results show that there were statistical differences ($p \leq 0.01$) between varieties and localities for all the characters evaluated. In expansion volume, the range of variation was from 6.2 to 10.6 ml $g^{-1}$. In the quality by popped grain size, 24 collections were outstanding in large and medium popped size.

**Keywords:** *Amaranthus cruentus*, *Amaranthus hypochondriacus*, hectoliter weight, grain weight.

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# Introduction

Mexico has a wide diversity in amaranth. For grain, there are the species *A. hypochondriacus* and *A. cruentus* (Espitia *et al*., 2010). In which wide morphological diversity between and within species has been reported (Espitia *et al*., 2012; de la O *et al*., 2012; Mapes *et al*., 2012; Ruiz *et al*., 2013). However, there are only 10 improved varieties of amaranth in Mexico (Córdova *et al*., 2019).

Amaranth grain is mainly consumed as popped grain (Escobedo-López *et al*., 2012). This process gives the grain better taste, color, aroma, protein digestibility and palatability (Dofing *et al*., 1990; Tovar *et al*., 1994; Zapotoczny *et al*., 2006; Morales *et al*., 2014). With amaranth popped grain, palanquetas, granolas and flours are made; with the flour, tortillas, bakery products, pastries, beverages, pasta for soup, extruded products or porridge are made (Morales *et al*., 2014). The use of a grain batch is determined depending on the obtained grain popping volume. For example, if the popping volume is high, it is ideal for the preparation of palanquetas and if the inflate is lower, the grain can be used in the production of flours or other products that are not affected by the expansion of the grain (Tavitas *et al*., 2011).

The grain popping is done in an artisanal way by means of a clay comal heated with fire and has yields of 30 to 40 kg per day, it is also done with a popping machine that uses a hot air fluidized bed system and a yield of 80 to 160 kg $ha^{-1}$ can be obtained (Muñoz *et al*., 2005). The use of the popping machine is the common method used in the industry because it is more efficient in the expansion volume achieved and in the amount of popped grain obtained (Vázquez *et al*., 1988; Murakami *et al*., 2014).

Grain expansion volume is affected by various factors among which are the growing environment, variety, popping method and processing conditions (Mishra *et al*., 2014; Ortiz-Torres *et al*., 2018; Ramírez-Pérez *et al*., 2018). In grain, the important characteristics are the thickness and content of bran, moisture content, type of endosperm, and physical characteristics of the grain (Chen and Yeh, 2001; Mishra *et al*., 2014).

In Mexico, the most important producing states occupy part of the basin of Mexico, Hidalgo, State of Mexico, Tlaxcala, Morelos, Puebla, Oaxaca and Michoacán, the average yields are between 1 100 and 1 400 kg $ha^{-1}$. As for the national production of amaranth, 51% of the production is obtained from Puebla, 22% from Morelos and the rest from Tlaxcala, Mexico City, State of Mexico and Guanajuato (Morales *et al*., 2014). In Puebla, the municipality with the largest area sown with amaranth in 2017 was Tochimilco with 1 160 ha (SIAP, 2017). Local populations of amaranth are primarily used in this region.

In Mexico, there is insufficient information on the factors affecting the expansion volume capacity of amaranth varieties under cultivation. Nor is there a sufficient assessment of the diversity in the grain-popping capacity of the local populations used.

The knowledge of the diversity in the expansion volume of the grain will allow selecting the best local genotypes for a better use of the grain. The only reports in Mexico are by Ortiz-Torres *et al*. (2018), who evaluated seven improved amaranth varieties and two outstanding populations in five localities of high valleys of Puebla and found that the best genotype was the local C2 population. In the state of Tlaxcala, Barrales-Domínguez and Torres-Hernández (1998) evaluated 35 accessions in two locations and found 12 outstanding accessions in volume of popped grain obtained.

In the state of Morelos, Tavitas *et al*. (2011) evaluated five varieties of amaranth of the *A. cruentus* species and found that the Amaranteca variety had the highest popped grain yield with 86.6% of efficiency. Vázquez *et al*. (1988) studied the behavior of 30 lines of *A. hypochondriacus* and *A. cruentus* and found outstanding lines in popping volume.

The selection and obtaining of varieties with greater expansion volume could increase the sale price of the grain because it could guarantee a greater potential in the grain popping volume and therefore greater amount of raw material for the preparation of the different products. The study was carried out in the municipality of Tochimilco, Puebla, the area with the largest area sown with amaranth in Mexico, with the aim of evaluating the behavior of the expansion volume of the popped grain in 36 local populations and improved varieties of amaranth.

## Materials and methods

Thirty-six populations and improved varieties of amaranth were evaluated. The 30 local populations were collected in the municipalities of Tochimilco, Cohuecan and Huaquechula, Puebla, Mexico during the 2018 agricultural cycle.

In the municipality of Tochimilco, the collections were carried out in the following localities: eight accessions were obtained in the municipal seat of Tochimilco, six in San Miguel Tecuanipa, five in Santiago Tochimizolco, four in San Lucas Tulcingo, one collection was obtained in the community of San Felipe Cuapexco municipality of Cohuecan, and one in Santiago Tetla, municipality of Huaquechula. Of the 30 populations, 29 are of the *A. hipochondriacus* species and only the C15 collection was of the *A. cruentus* species. Six improved varieties were included as controls: Amaranteca, Benito, Nutrisol and Revancha from the National Institute of Forestry, Agricultural and Livestock Research (INIFAP, for its acronym in Spanish) and the Laura and Gabriela varieties of the Technological Institute of the Altiplano of Tlaxcala (ITAT).

The Benito and Amaranteca varieties are of the *A. cruentus* species and are recommended for semitropical areas, the rest of the improved varieties are recommended for high valleys and are of the *A. hypochondriacus* species (Espitia *et al*., 2010). Four trials were established during 2015 and 2016 in San Lucas Tulcingo, San Miguel Tecuanipa, Santiago Tochimizolco and Tochimilco, all belonging to the municipality of Tochimilco. The geographical location of the trials is shown in Table 1.

**Table 1. Geographical location of the trial sites of amaranth populations and varieties, 2015 and 2016.**

| Locality | Latitude | Longitude | Altitude (m) |
|---|---|---|---|
| San Lucas Tulcingo | 18° 49’ 02.2” | 98° 37’ 17.3” | 2 061 |
| San Miguel Tecuanipa | 18° 88’ 11.11” | 98° 61’ 91.67” | 2 300 |
| Tochimilco | 18° 53’ 03.5” | 98° 32’ 4.2” | 1 961 |
| Santiago Tochimizolco | 18° 51’ 23.6” | 98° 37’ 25.2” | 2 197 |

Tochimilco has a temperature range of 2-20 °C, with a rainfall of 800-1 300 mm, has a temperate climate with rains in summer 69%, semi-cold subhumid with rains in summer 24%, cold 5% and semi-warm subhumid with rains in summer 2%.

In the area the following soil types are distinguished: Regosol 30%, Phaeozem 24%, Andosol 19%, Cambisol 12%, Durisol 5%, Leptosol 4% and Fluvisol 3% (INEGI, 2010). In 2015, the trials were sown in San Lucas Tulcingo on June 21 and in San Miguel Tecuanipa on June 6. In 2016, they were established in Tochimilco on July 18 and in Santiago Tochimizolco on June 17.

In all localities, the sowing was carried out in a way called mateada (placing a variable number of seeds per hole) every 20 cm, on the ridge of the furrow. A thinning of plants was carried out to leave a population of 100 000 plants $ha^{-1}$. Weed control was performed manually and with two hillings. The first was performed when the seedlings reached 10 to 15 cm in height and the second when the plants were 30 to 40 days old. A fertilization dose of 80N-40P-00K was used, applying everything in the first cultural practice. The experiments were conducted under rainfed conditions throughout the cultivation cycle.

The experimental unit consisted of two furrows five meters long and 0.8 m apart. A 6 x 6 square lattice design was used, with two repetitions in each locality. In the field, the following variables were measured: grain yield (YIE), it is the weight of clean grain at 10% of moisture and expressed in kilograms per hectare; days to mean male flowering (DMF), it is the number of days elapsed from sowing and until 50% of the population showed anthesis. Also, in a sample of five plants, the following was determined: plant height (PLH), which was the distance in centimeters from the ground to the tip of the spike; hectoliter weight (HLW), it was the volume occupied by the seed in a metal jar of 100 ml and was recorded in kilograms per hectoliter and weight of one thousand seeds (WTS), which was the weight in grams of a thousand seeds.

The evaluation of grain expansion was carried out according to the methodology proposed by Ramírez-Pérez *et al*. (2018). As a first step, samples of 15 g of raw grain were taken from each plot. The moisture content of each sample was determined by the oven method (2 g of grain at 130 °C in the convection oven per 2 h).

Depending on the moisture content of the sample, it was conditioned with the addition of the volume of distilled water required for the grain to reach 12% moisture, the water was added with a 1 ml syringe. The conditioning of the grain was carried out 24 hours before the popping. After grain conditioning, the samples were popped in a portable amaranth popping machine of the College of Postgraduates (Argumedo-Macías, 2019), which works by means of a fluidized bed with hot air. The air temperature used was 230-235 °C. Each observation was made in duplicate.

Once the popped grain was obtained, the following variables were measured. The Standard NMX-FF-116-SCFI-2010 was considered, which designates as popped grain the grain that is retained in a sieve with an opening of 1.19 mm. Therefore, the grain already popped was passed through the num. 16 sieve of physical tests (Montinox, Mexico), which has an opening of 1.19 mm. The variables that were determined were the following: Popped grain weight (POW), which is the weight (g) of the popped grain that was left on the 16 sieve; total expansion volume of popped grain (TVPO), which is the volume (ml) of the popped grain left on the 16 sieve, popped grain expansion volume (EXPV), which was calculated by dividing the TVPO by the original weight of the sample and expressed in ml $g^{-1}$ and popped grain yield (POGY), which was expressed as a percentage of weight and calculated by dividing the POW by the weight of the sample and multiplied by one hundred.

Expansion volume of small, popped grain (VSG), it is the volume of the popped grain that remained on the 16 sieve between the weight of the sample. The last three variables were expressed in ml $g^{-1}$. The weight was recorded with an Ohaus digital scale, and the volume was measured with a graduated cylinder of 10, 100 and 250 ml. To detect differences between treatments in each of the variables studied, a combined analysis of variance and a mean test with the Tukey test were performed. The Pearson correlation coefficient (r) was also determined to determine the degree of association between the variables studied. The analysis used the GLM procedure of the SAS version 9.0 program (SAS Institute, 2004).

## Results and discussion

The results of the combined analysis of variance (Table 2) show that in the factors of variation locality and varieties, there are highly significant statistical differences ($p \leq 0.01$) for all the characters evaluated. In the interaction of environment-genotype, highly significant statistical differences ($p \leq 0.01$) were found in almost all the variables evaluated, except in POGY and WTS, where there were no differences. The statistically significant differences observed between genotypes and between localities indicate important differences between populations and between assessment localities.

**Table 2. Mean squares and significance of the combined analysis of variance and coefficient of variation of the variables evaluated in amaranth accessions in four localities of Tochimilco, Puebla, Mexico. 2015 and 2016.**

| | Mean squares | | | | CV (%) |
|---|---|---|---|---|---|
| | Locality | Variety | Loc x Var | Error | |
| EXPV (ml $g^{-1}$) | 37.04 ** | 7.9 ** | 0.53 ** | 0.32 | 5.7 |
| POGY (%) | 789.34 ** | 16.37 ** | 6.38 ns | 5.85 | 2.9 |
| PNPO (%) | 73.75 ** | 3.8 ** | 2.38 ** | 1.45 | 46.1 |
| VSG (ml $g^{-1}$) | 33.07 ** | 5.51 ** | 0.26 ** | 0.12 | 11.7 |
| VMG (ml $g^{-1}$) | 28.76 ** | 8.38 ** | 0.66 ** | 0.31 | 11.3 |
| VLG (ml $g^{-1}$) | 20.54 ** | 3.5 ** | 0.61 ** | 0.4 | 34.1 |
| DMF | 6 738.73 ** | 74.62 ** | 18.69 ** | 10.15 | 4 |
| PLH (cm) | 60 602.92 ** | 1 234.79 ** | 354.96 ** | 213.32 | 10.2 |
| HLW (kg $hl^{-1}$) | 46.06 ** | 11.06 ** | 1.75 ** | 1.22 | 1.3 |
| WTS (g) | 0.13 ** | 0.03 ** | 0 ns | 0 | 3.8 |
| YIE (kg $ha^{-1}$) | 91 612.64 ** | 1577.55 ** | 902.25 ** | 524.72 | 37.5 |

**= significant at 0.01; *= significant at 0.5 probability; ns= not significant; Loc x Var= locality by variety; CV= coefficient of variation; EXPV= popped grain expansion volume; POGY= popped grain yield; PNPO= percentage of non-popped grain; VSG= expansion volume of small popped grain; VMG= expansion volume of medium popped grain; VLG= expansion volume of large popped grain; DMF= days to mean flowering; PLH= plant heigh; HLW= hectoliter weight; WTS= weight of one thousand seeds; YIE= grain yield.

Table 3 shows the averages by locality. The localities with the highest EXPV were Tochimilco and San Lucas Tulcingo. Secondly, Tecuanipa and at the end Tochimizolco. Barrales-Domínguez and Torres-Hernández (1998) consider that the capacity of grain to pop is a character of quantitative inheritance so there is a great influence of the environment on this character. In POGY, the locality with the lowest yield was Tochimilco. The quality by expanded grain size behaved as follows. The localities with the highest VLG and VMG were Tecuanipa and Tochimilco. On the other hand, the town with the highest VSG was San Lucas Tulcingo.

**Table 3. Averages of the variables evaluated in 36 amaranth accessions in four localities of Tochimilco, Puebla, Mexico in 2015 and 2016.**

| LOC | EXPV (ml $g^{-1}$) | PNPO (%) | POGY (%) | VSG (ml $g^{-1}$) | VMG (ml $g^{-1}$) | VLG (ml $g^{-1}$) | DMF | PLH (cm) | HLW (kg $hl^{-1}$) | WTS (g) | YIE (kg $ha^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| TOC | 10.3 a | 4.1 a | 79.2 b | 2.7 c | 5.2 ab | 2.3 a | 68.1 d | 113.2 c | 83.9 d | 0.909 c | 802 c |
| SLT | 10.1 a | 2 b | 86.3 a | 4 a | 5 b | 1.1 c | 90.1 a | 135.6 b | 85.8 a | 0.865 d | 1125 b |
| TEC | 10 b | 2.2 b | 85.8 a | 2.4 d | 5.4 a | 2.2 a | 78.4 c | 141.7 b | 84.7 c | 0.967 a | 2795 a |
| TZCO | 8.7 c | 2 b | 85.4 a | 3 b | 4 c | 1.8 b | 85.9 b | 182.7 a | 85.2 b | 0.927 b | 3002 a |
| HSD | 0.2 | 0.5 | 1 | 0.2 | 0.2 | 0.3 | 1.4 | 6.3 | 0.5 | 0.015 | 314 |

Means with equal letters are not statistically different (Tukey, 0.05). HSD= honest significant difference; LOC= locality; TOC= Tochimilco; SLT= San Lucas Tulcingo; TEC= San Miguel Tecuanipa; TZCO= Tochimizolco; EXPV= popped grain expansion volume; POGY= popped grain yield; PNPO= percentage of non-popped grain; VSG= expansion volume of small popped grain; VMG= expansion volume of medium popped grain; VLG= expansion volume of large popped grain; DMF= days to mean flowering; PLH= plant height; HLW= hectoliter weight; WTS= weight of one thousand seeds; YIE= grain yield.

There were also differences in agronomic characteristics between localities. In DMF, the locality of San Lucas Tulcingo was the latest and Tochimilco the earliest. In PLH, Tochimizolco had the tallest plants and Tochimilco the lowest. In HLW, the highest values were from Tulcingo and the lowest from Tochimilco. In WTS, the highest value was in Tecuanipa and the lowest in Tochimilco.

Regarding grain yield, the highest value was in Tochimizolco and the lowest in Tochimilco. In addition, it is observed that the locality with the highest yield, Tochimizolco, was the one with the lowest EXPV and on the contrary, the one with the lowest grain yield, Tochimilco, was the one with the highest EXPV. This apparent contradiction between grain yield and expansion volume has been previously reported by (Barrales-Domínguez and Torres-Hernández, 1989; Ortiz-Torres *et al*., 2018).

In popcorn, Dofing *et al*. (1990); Ceylan and Karababa (2002) reported that they obtained a larger size of grain popped with larger raw grains but the expansion volume of a sample of equal weight was greater with small grain than with large grain and they explain that it was because there are more small grains than large grains in a sample of equal weight.

Table 4 shows the means of the variables evaluated in the different genotypes. In EXPV, the mean of the superior group was between 9.5 to 10 ml $g^{-1}$. In the superior group were 22 of the 30 populations evaluated and the improved varieties Laura and Gabriela. In addition, it stands out that that the three genotypes that belong to the *A. cruentus* species, the Amaranteca and Benito varieties and the C15 population showed the lowest expansion volumes with 7.8, 6.6 and 6.2 ml $g^{-1}$, respectively.

**Table 4. Averages of the variables evaluated in 36 amaranth accessions in four localities of Tochimilco, Puebla, Mexico in 2015 and 2016.**

| Collection | EXPV (ml $g^{-1}$) | PNPO (%) | POGY (%) | VSG (ml $g^{-1}$) | VMG (ml $g^{-1}$) | VLG (ml $g^{-1}$) | DMF | PLH (cm) | HLW (kg $hl^{-1}$) | WTS (g) | YIE (kg $ha^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C2 | 10.6 a | 2.3 a | 84.7 a | 2.3 | 5.4 a | 2.9 a | 80.8 | 155.5 | 85.6 a | 0.951 a | 2511 a |
| C9 | 10.5 a | 2.3 a | 84.8 a | 2.3 | 5.5 a | 2.8 a | 83.6 | 152.1 | 85.8 a | 0.941 a | 1825 a |
| C18 | 10.5 a | 3.3 a | 83.9 a | 2.6 | 5.6 a | 2.4 a | 81.3 | 141.6 | 84.9 a | 0.936 a | 2312 a |
| C3 | 10.5 a | 2.2 a | 85.7 a | 2.4 | 5.7 a | 2.4 a | 81.9 | 148 | 85.5 a | 0.934 a | 1828 a |
| C6 | 10.4 a | 2.3 a | 85.2 a | 2.5 | 5.6 a | 2.3 a | 83.3 | 149.7 | 86.1 a | 0.945 a | 1795 a |
| C12 | 10.4 a | 2.2 a | 83.8 a | 2.5 | 5.6 a | 2.3 a | 83.1 | 141.7 | 85.4 a | 0.95 a | 1739 a |
| C24 | 10.4 a | 2.5 a | 84.4 a | 2.6 | 5.6 a | 2.1 a | 81.3 | 142.1 | 85.5 a | 0.948 a | 1656 a |
| C11 | 10.4 a | 2.3 a | 85 a | 2.5 | 5.6 a | 2.3 a | 83.5 | 163.2 | 85.2 a | 0.939 a | 2353 a |
| C10 | 10.3 a | 2.2 a | 85.4 a | 2.6 | 5.5 a | 2.3 a | 81.8 | 154.2 | 85.3 a | 0.92 | 2306 a |
| C7 | 10.3 a | 2.4 a | 84.6 a | 2.6 | 5.5 a | 2.2 a | 82.9 | 152.7 | 85 a | 0.931 a | 2005 a |
| C1 | 10.3 a | 2.6 a | 85 a | 2.6 | 5.6 a | 2.1 a | 80.8 | 150.2 | 85.2 a | 0.931 a | 1939 a |
| C4 | 10.3 a | 2.7 a | 84.2 a | 2.3 | 5.6 a | 2.4 a | 81 | 152.3 | 85.2 a | 0.961 a | 1946 a |
| C21 | 10.2 a | 1.9 a | 84.6 a | 2.9 | 5.7 a | 1.6 | 82.5 | 143.2 | 84.8 a | 0.911 | 1791 a |
| C14 | 10.2 a | 2.4 a | 84.5 a | 2.5 | 5.2 a | 2.5 a | 82.3 | 149.8 | 85.3 a | 0.953 a | 2022 a |
| C8 | 10.2 a | 2.1 a | 85.4 a | 2.6 | 5.2 a | 2.4 a | 81 | 148.8 | 85.3 a | 0.945 a | 1797 a |
| C27 | 10.1 a | 2.4 a | 83.9 a | 4.3 a | 4.5 | 1.3 | 84.1 | 132.8 a | 85.2 a | 0.789 | 1764 a |
| C5 | 10.1 a | 2.6 a | 83.3 a | 2.4 | 5.4 a | 2.3 a | 82.8 | 150.8 | 85.1 a | 0.981 a | 1864 a |
| C19 | 10.1 a | 2.1 a | 84.7 a | 2.7 | 5.6 a | 1.8 a | 80.6 | 160.7 | 85.1 a | 0.947 a | 2409 a |
| C29 | 10 a | 2.6 a | 83.8 a | 3.2 | 5.1 a | 1.7 a | 80.9 | 149 | 85.9 a | 0.872 | 1754 a |
| C28 | 10 a | 2.7 a | 84.6 a | 2.5 | 5.5 a | 2.1 a | 79.8 | 142 | 85.6 a | 0.984 a | 1925 a |
| C23 | 10 a | 2.3 a | 84.9 a | 2.7 | 5.3 a | 1.9 a | 80.6 | 145.5 | 85.5 a | 0.968 a | 2391 a |
| Laura | 10 a | 2.2 a | 85.6 a | 4.7 a | 4.5 | 0.8 | 80.9 | 132.4 a | 84.7 a | 0.761 | 2643 a |
| C13 | 9.9 a | 3.1 a | 83.8 a | 2.4 | 5 | 2.5 a | 84.1 | 147.7 | 84.6 a | 0.946 a | 1623 a |
| Gabriela | 9.9 a | 2.1 a | 85.1 a | 4.7 a | 4.4 | 0.8 | 77.9 a | 113.3 a | 85 a | 0.779 | 1828 a |
| C20 | 9.9 a | 2.1 a | 86.7 a | 2.9 | 5.2 a | 1.8 a | 79.6 | 137.8 | 85.2 a | 0.946 a | 2177 a |
| C16 | 9.9 a | 2.4 a | 84.4 a | 2.6 | 5.5 a | 1.8 a | 82.9 | 146.9 | 85.6 a | 0.928 a | 2208 a |
| C25 | 9.8 a | 2.6 a | 84.3 a | 2.7 | 5.4 a | 1.7 a | 82.5 | 151.4 | 84.9 a | 0.95 a | 2386 a |
| C30 | 9.7 a | 2.3 a | 84.6 a | 4.1 | 4.2 | 1.4 | 81.5 | 135.1 a | 85 a | 0.798 | 2608 a |
| C22 | 9.5 a | 2.3 a | 84.1 a | 3 | 5.2 | 1.3 | 80.9 | 149.3 | 85.1 a | 0.931 a | 2141 a |
| C26 | 9.5 | 3.4 a | 82.3 a | 2.7 | 4.7 a | 2.1 a | 82.3 | 149.9 | 85.5 a | 0.958 a | 1420 a |
| C17 | 9.4 | 2.1 a | 83.4 a | 2.3 | 5 a | 2.1 a | 80.1 | 150.5 | 85.6 a | 0.994 a | 2078 a |
| Revanch | 9.3 | 4 a | 82.7 a | 2.6 | 4.4 | 2.3 a | 73 a | 107.7 a | 83.4 | 0.948 a | 1583 a |
| Nutrisol | 8.9 | 2.4 a | 84.3 a | 4.9 a | 3.1 | 0.8 | 75.3 a | 137.4 | 84.5 a | 0.787 | 2271 a |
| Benito | 7.8 | 3.7 a | 83.2 a | 4.8 a | 2.5 | 0.5 | 72.9 a | 121.2 a | 81.1 | 0.824 | 858 |

| Collection | EXPV (ml g$^{-1}$) | PNPO (%) | POGY (%) | VSG (ml g$^{-1}$) | VMG (ml g$^{-1}$) | VLG (ml g$^{-1}$) | DMF | PLH (cm) | HLW (kg hl$^{-1}$) | WTS (g) | YIE (kg ha$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Amaran | 6.6 | 4.2 a | 81.6 | 4.5 a | 1.7 | 0.4 | 73.9 a | 120.2 a | 81.6 | 0.861 | 723 |
| C15 | 6.2 | 5.1 | 78.1 | 3.6 | 2.1 | 0.5 | 74.5 a | 132.2 a | 81.4 | 0.956 a | 1034 |
| HSD | 1.1 | 2.4 | 4.7 | 0.7 | 1.1 | 1.2 | 6.2 | 28.6 | 2.2 | 0.069 | 1421 |

a= means belonging to the statistically superior group ($p \leq 0.5$); HSD= honest significant difference. Revanch= Revancha; Amaran= Amaranteca; EXPV= popped grain expansion volume; POGY= popped grain yield; PNPO= percentage of non-popped grain; VSG= expansion volume of small, popped grain; VMG= expansion volume of medium popped grain; VLG= expansion volume of large popped grain; DMF= days to mean male flowering; PLH= plant height; HLW= hectoliter weight; WTSM= weight of one thousand seeds; YIE= grain yield.

In PNPO, the population with the highest average was C15 with 5.1 g. While in POGY, a variation of 78.1 to 86.7% was observed. The only varieties that were not in the superior group were Amaranteca and C15. The observed popped grain yield is below that obtained by Tavitas *et al*. (2011), who reported yields between 83.3 and 86.6% in varieties of *A. cruentus*. In the quality by popped grain size, it stands out that 25 collections stood out in VLG and VMG. Only the improved variety Revancha was in the superior group in VLG. Twenty-four collections were also outstanding in VLG and VMG at the same time.

This shows the potential of local varieties of Tochimilco as a source of germplasm to select by EXPV. Obtaining a high volume of expansion and expanded grain of larger size is important because this is associated with an increase in final volume and palatability (Dofing *et al*., 1990). On the other hand, the C21, C8 collections and the Laura, Gabriela, Nutrisol, Benito and Amaranteca varieties had the group with the highest amount of VSG.

Regarding agronomic characteristics, variation between genotypes was observed in the characteristics evaluated. In YIE, it had a range of 723 to 2 643 kg ha$^{-1}$ and only C15, Benito and Amaranteca were not part of the superior group. The low grain yield and EXPV reflects a lack of adaptation of these varieties to the environmental conditions of the municipality of Tochimilco. In DMF, the interval was 72.9 to 84.1 days. If this period of 11.3 days is divided into three parts. It can be seen that 27 genotypes were in the latest portion, in this group most were local populations and the Laura variety.

In the intermediate portion were four local genotypes and the Gabriela variety. In the earliest extract were the Nutrisol, Amaranteca, Revancha, Benito varieties and the C15 collection. This characteristic in these varieties is explained because they were selected for their precocity to adapt to a wide environmental range (Espitia *et al*., 2010). In PLH, there was a variation from 107.7 to 163.2 cm and almost all local populations were in the group with the highest height along with the Nutrisol variety. The plants of lower height were the Amaranteca, Benito and Revancha varieties and the C27, C30 and C15 collections. In HLW, all the local populations and the Laura, Gabriela and Nutrisol varieties were in the outstanding group. In WTS, 25 local populations and the Revancha variety were in the superior group.

Table 5 shows the correlations between the variables evaluated. It is observed that EXPV correlated positively and statistically significantly ($p \leq 0.01$) with variables that measured the efficiency in the amount of grain that popped, such as POGY (r= 0.19$^{**}$) and PNPO (r= -0.22$^{**}$). Also, EXPV correlated positively and highly significantly ($p < 0.01$) with quality-related variables by popped grain size such as VMG (r= 0.85$^{**}$) and VLG (r= 0.55$^{**}$), but negatively correlated with VSG (r= -0.35$^{**}$), so higher EXPV was associated with higher volume of large and medium popped grain and with lower percentage of non-popped grain (Dofing *et al*., 1990; Soylu and Tekkanut, 2007).

**Table 5. Coefficients of linear correlation between the variables evaluated.**

| | PNPO | POGY | VSG | VMG | VLG | DMF | PLH | HLW | WTS | YIE |
|---|---|---|---|---|---|---|---|---|---|---|
| EXPV | -0.22 ** | 0.19 ** | -0.35 ** | 0.85 ** | 0.55 ** | 0.03 ns | -0.25 ** | 0.41 ** | 0.08 ns | -0.14 * |
| PNPO | | -0.79 ** | 0.01 ns | -0.26 ** | 0.03 ns | -0.5 ** | -0.41 ** | -0.47 ** | -0.05 ns | -0.41 ** |
| POGY | | | 0.07 ns | 0.17 ** | -0.05 ns | 0.61 ** | 0.4 ** | 0.42 ** | 0 ns | 0.42 ** |
| VSG | | | | -0.57 ** | -0.77 ** | 0.16 ** | -0.21 ** | -0.15 * | -0.85 ** | -0.23 ** |
| VMG | | | | | 0.40 ** | 0.06 ns | -0.08 ns | 0.44 ** | 0.36 ** | -0.01 ns |
| VLG | | | | | | -0.2 ** | 0.01 ns | 0.11 ns | 0.53 ** | 0.09 ns |
| DMF | | | | | | | 0.51 ** | 0.53 ** | -0.06 ns | 0.21 ** |
| PLH | | | | | | | | 0.36 ** | 0.3 ** | 0.69 ** |
| HLW | | | | | | | | | 0.11 ns | 0.28 ** |
| WTS | | | | | | | | | | 0.25 ** |

$^{**}$= significant at 0.01 of probability; $^{*}$= significant at 0.05 of probability, ns= not significant; EXPV= popped grain expansion volume; POGY= popped grain yield; PNPO= percentage of non-popped grain; VSG= expansion volume of small popped grain; VMG= expansion volume of medium popped grain; VLG= expansion volume of large popped grain; DF= days to mean male flowering; PLH= plant height; HLW= hectoliter weight; WTS= weight of one thousand seeds; YIE= grain yield.

EXPV was negatively and statistically significantly associated ($p < 0.01$) with the agronomic variables PLH (r= -0.25$^{**}$) and YIE (r= -0.14$^{*}$); but positively with HLW (r= 0.41$^{**}$). The hectoliter weight is a way to evaluate the quality of grain (Bern and Brumm, 2009), so with higher HLW, a better response is noticed in the quality and quantity of popped grain.

In quality of popped grain by size, it was observed that VSG correlated negatively with the variables VMG (r= -0.57$^{**}$) and VLG (r= -0.77$^{**}$) and it is clear since they are exclusive variables, greater volume of grain popped of small size is opposed to the volume of medium and large grain. Likewise, VSG correlated negatively with agronomic variables PLH (r= -0.21$^{**}$), HLW (r= -0.15$^{*}$), WTS (r= -0.85$^{**}$) and positively correlated with DMF (r= 0.16$^{**}$). There was more small-sized popped grain with materials with low HLW, WTS and PLH. For its part, VMG was positively associated with popping variables VLG (r= 0.4$^{**}$) and with agronomic variables HLW (r= 0.44$^{**}$) and WTS (r= 0.36$^{**}$).

The YIE variable correlated positively and significantly ($p\leq$ 0.01) with variables that measured the popping PNPO (r= -0.41$^{**}$) and POGY (r= 0.42$^{**}$) and negatively with VSG (r= -0.23$^{**}$). Therefore, materials with a higher percentage of grain from the sample that popped was associated with better grain yield. In the same way, YIE was associated with the agronomic variables DMF (r= 0.21$^{**}$), PLH (r= 0.69$^{**}$), HLW (r= 0.28$^{**}$), WTS (r= 0.25$^{**}$), these variables are indicators of plant vigor and yield components. On the other hand, DMF was associated with agronomic variables PLH (r= 0.51$^{**}$) and HLW (r= 0.53$^{**}$). Latest plants had higher plant height and hectoliter weight. Finally, PLH correlated positively with the agronomic variables HLW (r= 0.36$^{**}$) and WTS (r= 0.3$^{**}$).

On the other hand, the weight of one thousand seeds can be a useful characteristic for predicting the size of the popped grain to be obtained; because WTS correlated positively with VLG (r= 0.53$^{**}$), VMG (r= 0.36$^{**}$), and correlated negatively and highly significantly with VSG (r= -0.85$^{**}$). That is, with grains of greater weight, greater yield of expanded grain of large and medium size was obtained. In popcorn, Soylu and Tekkant (2007) evaluated three grain sizes and found that large grains give a larger popped grain compared to small grains. For their part, Song *et al*. (1991), when evaluating five grain sizes in four genotypes, found that medium-sized grains had the highest popping volume. In amaranth Vázquez *et al*. (1988) found that grain with better weight has higher popping volume.

## Conclusions

Highly significant statistical differences ($p\leq$ 0.01) were observed between varieties for all the characters evaluated, which indicates important differences between the evaluated populations. In expansion volume, the range of variation was from 6.2 to 10.6 ml $g^{-1}$, the superior group was formed by 22 of the 30 local populations evaluated and the improved varieties Laura and Gabriela.

In the quality by popped grain size, it stands out that 24 collections and no improved variety were outstanding at the same time in large and medium popped size. This shows the potential of local populations of Tochimilco as a source of germplasm to select by volume of expansion.

The hectoliter weight and weight of one thousand seeds are characteristics that are associated with the behavior of the expansion volume and the size of popped grain. Higher HLW was associated with higher popped grain volume (r= 0.41$^{**}$), higher proportion of medium popped size (r= 0.44$^{**}$) and better popping yield POGY (r= 0.42$^{**}$). Also, higher grain weight was correlated with higher yield of expanded grain of large (r= 0.53) and medium size VMG (r= 0.36).

## Cited literature

Argumedo, M. A. 2019. Reventadora de semilla de amaranto (*Amaranthus* sp). Agroproductividad. 12(11):111-113. https://doi.org/10.32854/agrop.vi0.1541.

Barrales, D. J. S. y Torres, H. L. 1998. Capacidad de reventado del grano de amaranto (*Amaranthus hipochondriacus* L.) producido en dos ambientes de temporal. Rev. Chapingo Ser. Hortic. 4(1):63-66.

Espitia, R. E.; Escobedo, L. D.; Mapes, S. C.; De la O, O. M.; Aguilar, D. M.; Hernández, J. M.; Ayala, A. V.; Rivas, V. P.; Martínez, T. G.; Ramírez, V. M. y Morán, S. H. 2012. Conservación de los recursos genéticos de amaranto (*Amarantus* spp.) en México. *In*: Espitia, R. E. (Ed.). Amaranto: Ciencia y Tecnología. INIFAP/SINAREFI. Libro científico núm. 2. Celaya, Guanajuato, México. 147-163 pp.

Espitia, R. E.; Mapes, S. C.; Escobedo, L. D., De la O, O. M.; Rivas, V. P.; Martínez, T. G.; Cortés, E. L. y Hernández, J. M. 2010. Conservación y uso de los recursos genéticos de amaranto en México. SINAREFI-INIFAP-UNAM. Celaya, Guanajuato, México. 101 p.

Córdova, T. L.; Vásquez, V. M. y Rosario, R. J. 2019. Catálogo nacional de variedades vegetales 2019. Servicio Nacional de Inspección y Certificación de Semillas. Secretaría de Agricultura y Desarrollo Rural. Edición 2019. Ciudad de México. México. 106 p.

Ceylan, M. and Karababa, E. 2002. Comparison of sensory properties of popcorn from various types and sizes of kernel. J. Sci. Food Agric. 82(1):127-133.

Chen, C. M. and Yeh, A. I. 2001. Effect of amylose content on expansion of extruded rice pellet. Cereal Chemistry. 78(3):261-266.

De la O, O. M.; Espitia, R. E.; Ayala, A. V.; Hernández, J. M.; Arellano, J. L. y Ruiz, V. C. 2012. Caracterización del germoplasma para grano de amaranto (*Amaranthus* spp.). *In*: Espitia, E. (Ed.). Amaranto: ciencia y tecnología. INIFAP/SINAREFI. Libro científico núm. 2. Celaya, Guanajuato, México. 165-181 pp.

Dofing, S. M.; Thomas, C. M. A. and Buck, J. S. 1990. Genotype X popping method interaction for expansion volume in popcorn. Crop Sci. 30(1):62-65.

Escobedo, L. D.; Ayala, A. V. y Campos, S. G. 2012. Formas de consumo del amaranto en México. *In*: Espitia, E. (Ed.). Amaranto: ciencia y tecnología. INIFAP/SINAREFI. Libro científico núm. 2. Celaya, Guanajuato, México. 341-354 pp.

INEGI. 2010. Instituto Nacional de Estadística y Geografía. Prontuario de información geográfica municipal de los Estados Unidos Mexicanos. Tochimilco, Puebla. Clave geoestadística. 21188. 1-10 pp.

Mishra, G.; Joshi, D. C. and Panda, B. K. 2014. Popping and puffing of cereal grains: a review. J. Grain Processing Storage. 1(2):34-46.

Moreno, M. G.; Herrera, T. S.; Licea, E. M. y De la O, O. M. 2015. Comparación entre el uso de aire caliente y microondas sobre la capacidad de reventado de semilla en cuatro variedades de Amaranto (*Amaranthus* sp.). Rev. Ingeniantes. 1(2):40-44.

Murakami, T.; Yutani, A.; Yamano, T.; Iyota, H. and Konishi, Y. 2014. Effects of popping on nutrient contents of amaranth seed. Plant foods for human nutrition. 69(1):25-29. https://doi.org/10.1007/s11130-013-0392-7.

Norma Mexicana NMX-FF-114-SCFI. 2009. Grano de amaranto (*Amaranthus* spp.) para uso y consumo humano, especificaciones y métodos de ensayo. SAGARPA-DGN. México, DF. 36 p.

Mapes, S. C.; Díaz, O. A. y Blancas, J. 2012. Caracterización de germoplasma de amaranto (*Amaranthus* spp.) para verdura. *In*: Espitia, R. E. (Ed.). Amaranto: ciencia y tecnología. INIFAP/SINAREFI. Celaya, Guanajuato, México. Libro científico núm. 2. 183-201 pp.

Muñoz, G. F.; Gaytán, J. G.; Lugo, A. M.; Martínez, R. J. y Flores, J, E. 2005. Fabricación de una máquina para reventar granos de amaranto. Rev. Cienc. Téc. Agropec. 14(4):1-8.

Ortiz, T. E.; Argumedo, M. A.; García, P. H.; Meza, V. R.; Bernal, M. R. y Taboada, G. O. R. 2018. Rendimiento y volumen de expansión de grano de variedades mejoradas de amaranto para valles altos de Puebla. Rev. Fitotec. Mex. 41(3):291-300. https://www.redalyc.org/jatsRepo/610/61059021009/61059021009.pdf.

Ramírez, P. A.; Ortiz, T. E.; Argumedo, M. A.; de la O-Olán, M.; Jacinto, H. C.; Ocampo, F. I y Díaz, R. R. 2018. Método para evaluar reventado de grano en amaranto. Rev. Mex. Cienc. Agríc. 9(3):675-682. Doi: 10.29312/remexca.v9i3.1224.

Ruíz, V. C.; De la O, O. M.; Espitia, R. E.; Sangerman, J. D. M.; Hernández, J. M. y Scwentesius, R. R. 2013. Variabilidad cualitativa y cuantitativa de accesiones de amaranto determinada mediante caracterización morfológica. Rev. Mex. Cienc. Agríc. 4(5):789-801. https://www.redalyc.org/pdf/2631/263127573011.pdf.

SAS Institute 2004. SAS/SATA 9.9. User's Guide. SAS Institute Inc. Cary, NC. 1731-1900 pp.

SIAP. 2017. Servicio de Información Agroalimentaria y Pesquera. Producción Agrícola. Servicio de Información Agroalimentaria y Pesquera, SAGARPA. Ciudad de México. http://www.gob.mx/siap/accio-nes-y-programas/produccion-agricola-33119.

Song, A.; Eckhoff, S. R.; Paulsen, M. and Litchfield, J. B. 1991. Effects of kernel size and genotype on popcorn popping volume and number of unpopped kernels. Cereal Chemistry. 68(5):464-467.

Soylu, S. and Tekkanat, A. 2007. Interactions amongst kernel properties and expansion volume in various popcorn genotypes. J. Food Eng. 80(1):336-341.

Tavitas, F. L.; Valle, V. M. y Hernández, R. L. 2011. Determinación de la calidad del grano reventado y contenido de aceite en cinco variedades de amaranto. Campo Experimental Zacatepec- Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Folleto técnico núm. 53. México, DF. 34 p.

Zapotoczny, P.; Markowski, M.; Majewska, K.; Ratajski, A. and Konopko, H. 2006. Effect of temperature on the physical, functional, and mechanical characteristics of hot-air-puffed amaranth seeds. J. Food Eng. 76(4):469-476. https://doi.org/10.1016/j.jfoodeng.2005.05.045.